University of Alberta

Biological Nutrient Removal in a Submerged Membrane Bioreactor

by

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For my family,
Jinghong Kang and Tianchu Liu

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List of Abbreviations

AE	Anaerobic
AN	Anoxic
AO	Aerobic
ASA	Activated sludge analysis using a microscope
BNR	Biological nutrient removal
BOD_5	Five-day carbonaceous biochemical oxygen demand
CAS	Conventional activated sludge system
COD	Chemical oxygen demand
DO	Dissolved oxygen
F/M	Food / microorganism ratio
GBWWTP	Gold Bar Wastewater Treatment Plant
HRT	Hydraulic retention time
MBR	Membrane bioreactor
MLSS	Mixed liquor suspended solids
MLVSS	Mixed liquor volatile suspended solids
MT	Membrane tank
NH_3-N	Ammonia nitrogen
NO_3^--N	Nitrate nitrogen
PE	Primary effluent
PHB	Polydroxybutyrates, an energy-storage compound
PO_4^{3-}-P	Ortho-phosphate phosphorus
PR	Pre-anoxic
RAS	Returned activated sludge
rbCOD	Readily biodegradable COD
sCOD	Soluble COD
SOCR	Specific oxygen consumption rate, the amount of oxygen consumed by 1 gram of MLVSS (bacteria) per hour
SRT	Solids retention time
SSVI	Specific sludge volume index, the volume occupied by 1 gram of mixed liquor after 30 minutes of settling
TFL	Total filamentous length measured by means of a hemocytometer
TKN	Total Kjeldahl nitrogen (Org N + NH_4^+)
TMP	Transmembrane pressure
TN	Total nitrogen
TOXN	Total oxidized nitrogen (NO_2^- + NO_3^+)
TP	Total phosphorus
TSS	Total suspended solids
UCT	University of Cape Town
VFA	Volatile fatty acids
VIP	Virginia Initiative Plant
VSS	Volatile suspended solids
WS	Wasting sludge

1 Introduction

Enforcement of more stringent legislation leads to more research on methods to protect receiving waters from contaminations and eutrophication. The increasing scarcity of water sources also stimulates the interest for new technologies for wastewater reuse and reclamation. One of major innovative technologies in municipal wastewater treatment industry is the biological nutrient removal (BNR), which reduces the amount of nutrients (phosphorus and nitrogen) in wastewater effluents by means of a biological process. The BNR process, in combination with a membrane bioreactor (MBR), has been the main focus for many studies in municipal wastewater treatment field in recent years.

BNR-MBR process is a combination of an activated sludge process and membrane separation. It is one of the most promising approaches to the municipal wastewater treatment with four advantages: high compactness, high quality of the effluent, high hydraulic loading and low sludge production. Due to recent technical innovations and significant cost reductions, the applicability for the MBR technology in municipal wastewater treatment has increased. The wide application of BNR-MBR systems for municipal wastewater treatment is expected in the coming days.

In co-operation with Gold Bar Wastewater Treatment Plant (GBWWTP), University of Alberta (Department of Civil & Environmental Engineering) has been investigating the biological nutrient removal in membrane bioreactors (MBR). The first investigation was carried out by Mr. Geoffry Heise. The initial results indicated good BOD and ammonia reduction. However, poor biological phosphorus reduction and nitrate reduction were

observed. Further research was needed to improve the bio-P and denitrification processes. This thesis project undertook the task of continuing the research on BNR using bench-scale submerged membrane bioreactors.

Based on the previous study, two new bench-scale membrane bioreactors (118 litre each) was designed, constructed and operated to treat municipal wastewater at GBWWTP. Two different BNR bioreactor configurations (GBWWTP process and University of Cape Town (UCT) process) were applied. GBWWTP process was adapted to MBR1 and UCT process was adapted to MBR2. Both MBRs were operated over a 92 day study period at three hydraulic stages (HRTs of 4, 6 and 8 hours) and with an average sludge age of 15 to 20 days. High permeate flux rate (30 L/m^2 h) was reached during the study for 36 days. Due to the extensive efforts required on the MBR units operation, most of sample analyses were carried out by the GBWWP laboratory. Zenon hollow fibre membranes with pore size of 0.04 mm (ZW-10) were used. The performance of the membrane bioreactors on membrane integrity, disinfections, TSS, BOD, COD, especially nitrogen and phosphorus reduction, were closely observed and evaluated. The primary objective of the research was to find out the efficiency of this BNR-MBR technology for optimum biological nutrient reduction in submerged membrane bioreactors for Gold Bar municipal wastewater.

2 Literature Review

2.1 New Legislation and Wastewater Reclamation Demands

Over 640,000 people from Edmonton area are serviced by the GBWWTP, and approximately 100 billion litres of wastewater were treated and discharged to the North Saskatchewan River each year. Most of wastewater sources are domestic households; other sources are from infiltration flows, street runoff, commercial, industrial and institutional establishments. The primary treatment capacity is 910 million litres per day (ML/day) with an average treatment of 310 ML/day. The peak secondary treatment capacity is 420 ML/day.

By the year 2005, the new legislation by Alberta Environment requires the Gold Bar plant to meet new limits. The limit of total phosphorus concentration shall be 1 mg/L and ammonia nitrogen limits shall be 10 mg/L in the winter (November to April) and 5 mg/L in the summer (May to October). GBWWTP averaged concentrations for the licensed parameters in 2003 are compared to both the current limits and the new limits for 2005 as indicated in Table 1.

In order to meet the new limits, all existing secondary aeration tanks have been converted to bioreactors with full scale biological nutrient removal (BNR) processes. With BNR retrofit, the nutrients in the effluent, like phosphorus and ammonia-nitrogen, are reduced. However, the new BNR systems also encountered problems of NH_3-N reduction, especially during winter and spring operating periods, largely due to cold temperatures

and runoff, which leads to lower nitrifier kinetics and concentration in the mixed liquor of bioreactors.

Table 1. GBWWTP averaged concentrations for licensed parameters in 2003 in comparison with both the current limits and 2005 limits.

Parameter	2003 average concentration	Current limit	2005 limit
BOD_5 (mg O_2/L)	4.5	≤ 25.0	≤ 20.0
TSS (mg/L)	7.9	≤ 25.0	≤ 20.0
Fecal Coliform (CFU/100mL)	142	≤ 200	≤ 200
TP (mg/L)	0.9	No limit	≤ 1.0
NH_3-N Winter (mg/L)	12.7	No limit	≤ 10.0 (winter)
NH_3-N Summer (mg/L)	9.5	No limit	≤ 5.0 (summer)

In recent years several external customers in neighboring industries have expressed interest in using the Gold Bar effluent as an alternative source for cooling and boiler process water. City of Edmonton has also expressed interest in wastewater reclamation for landscape irrigation, and municipal recreational ponds. These movements drive municipal wastewater industry to new technologies to improve the effluent quality. Membrane bioreactor (MBR) becomes one of the alternative processes to upgrade municipal wastewater treatment facilities.

2.2 Quality Parameters of Current BNR Process at GBWWTP

The average BNR quality parameters and reduction efficiencies were summarized in Table 2 from GBWWTP process data for raw influent, primary effluent and combined final effluent, respectively. The operation period covered the entire months of January, February, March and April of 2004.

Table 2. GBWWTP average influent & effluent quality parameters and removal efficiencies (January to April, 2004).

Parameter	Units	Raw Influent	Primary Effluent	Reduction rate (%)	Final Effluent	Reduction rate (%)
BOD	mg/L O_2	247	147	41%	4.5	97%
COD	mg/L O_2	578	312	46%	40.4	87%
NH_3-N	mg/L N	25	22	13%	7.8	64%
TKN	mg/L N	44	36	17%	11.3	69%
NO2+NO3	mg/L N	0.03	0.17	N/A	10	N/A
Total P	mg/L P	7	7	-7%	0.77	90%
TSS	mg/L	250	116	54%	7	94%
TN	mg/L N	44	36	17%	21	41%

From Heise (2004)

The concentration of biodegradable organic matter relative to the nutrient concentrations in an influent wastewater can dramatically affect the performance of a BNR system. This is because of the key role biodegradable organic matter plays in nutrient removal. Relationships between expected biological nutrient removal efficiency and ratios of wastewater organic matter to nutrient are indicated in Table 3 (Grady *et al.*, 1999).

Table 3. Relationship between expected biological nutrient removal efficiency and influent organic matter to nutrient ratios.

Nutrient removal efficiency	COD/TKN	BOD5/NH3-N	BOD5/TKN	BOD5/ΔP	COD/ΔP
Poor	< 5	< 4	< 2.5	> 25	> 43
Moderate	5 to 7	4 to 6	2.5 to 3.5	20 to 25	34 to 43
Good	7 to 9	6 to 8	3.5 to 5		
Excellent	> 9	> 8	> 5	15 to 20	26 to 34

2.3 Biological Nutrient Removal

Nutrients in wastewater treatment refer to the elements nitrogen and phosphorus, which are essential to the growth of microorganisms, plants, and animals. The term "biological nutrient removal" (BNR) is used to describe the removal of nitrogen and phosphorus in biological treatment processes for wastewater treatment. Biological nutrient removal processes are incorporated into the activated sludge process with anoxic and /or anaerobic zones to provide nitrogen and /or phosphorus removal. Many BNR variants have been developed, representing a wide range of nutrient removal capabilities (Grady *et al.*, 1999). Specialized bacteria population responsible for nitrogen or phosphorus reduction can be cultured by optimizing the growth environmental conditions of the activated sludge.

2.3.1 Biological Nitrogen Removal

Nitrogen removal by biological means (that is, nitrification-denitrification) can be very effective and is made possible by anoxic aerobic sequencing in activated-sludge processes in biological nutrient removal (Stevens *et al.*, 2002).

2.3.1.1 Sources and Forms of Nitrogen

Nitrogen compounds come from three principle sources: (1) the nitrogenous compounds of plant and animal origin, (2) sodium nitrate, and (3) atmospheric nitrogen. Most of nitrogen sources in soil/groundwater originate from biological systems. There are unoxidized and oxidized forms of nitrogen in the environment. Unoxidized forms of nitrogen include nitrogen gas (N_2), ammonia (NH_4^+, NH_3) and organic nitrogen (urea,

amino acids, peptides, proteins, etc...). Oxidized forms of nitrogen include nitrite (NO_2^-), nitrate (NO_3^-), nitrous oxide (N_2O), nitric oxide (NO) and nitrogen dioxide (NO_2). The nitrogen in organic compounds is readily converted to ammonia through the action of microorganisms in the aquatic or soil environment. The distribution of the ammonia species depends on the pH in aqueous solution. The dominating form of ammonia (NH_3) in typical municipal wastewater is primarily ammonium ions (NH_4^+). Nitrate nitrogen is the most oxidized form of nitrogen in wastewaters. The concentration of nitrates may range from 0 to 20 mg/L as N in wastewater effluents.

2.3.1.2 Biological Nitrification Process

Biological nitrification is a two-step biological process in which ammonia (NH_4-N) is oxidized to nitrite (NO_2-N) and nitrite is oxidized to nitrate (NO_3^--N). Under aerobic conditions, autotrophic bacteria convert ammonia to nitrite and then nitrate utilizing oxygen as a terminal electron acceptor and consuming alkalinity in two oxidative reactions known as nitritation and nitratation (Stevens *et al.*, 2002):

Nitritation: $NH_4^+ + 2O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$

Nitratation: $2NO_2 + O_2 \rightarrow 2NO_3^-$

Overall reaction: $2NH_4^+ + 4O_2 \rightarrow 2NO_3^- + 4H^+ + 2H_2O$

Many aerobic autotrophic bacteria are capable of oxidizing ammonia and responsible for the above two-step process. Two common nitrification bacteria genera are *Nitrosomonas* for nitritation and *Nitrobacter* for nitratation (Sharma and Ahlert, 1977). Both genera of bacteria are strict aerobes and will not grow in the absence of oxygen. Sufficient length of sludge age should be maintained to allow the growth of nitrifying bacteria for the

nitrification to occur (Ekama *et al.*, 1983). The oxidation rate of ammonia nitrogen is typically the rate-limiting step under steady-state conditions (Stenstrom and Song, 1991).

4.57 mg of O_2 are consumed by the nitrifying bacteria and 7.14 mg of alkalinity (as $CaCO_3$) are destroyed when each milligram of NH_4^+-N is oxidized to nitrate. Therefore, sufficient O_2 and alkalinity are required to be present for nitrification to occur. Nitrification rates increase up to DO concentrations of 3 to 4 mg/L. A reactor DO concentration of 2.0 mg/L is commonly used. At DO concentrations below 0.50 mg/L, nitrification rates are greatly inhibited and the low DO inhibition effect was reported to be greater for *Nitrobacter* than for *Nitrosomonas*, where increased NO_2-N concentrations were found in effluent with incomplete nitrification. An optimal DO range of 1.5 to 3.0 mg/L is also reported for good phosphorus reduction. If the DO is too high, the denitrification may be reduced, especially in the small pre-anoxic zone of the GBWWTP process, resulting in nitrate being discharged to the anaerobic zone. But if the DO is too low, the phosphorus reduction efficiency may be reduced due to incomplete ortho-phosphate uptake in the aerobic zone, or nitrification may be reduced too and the sludge settling properties may also deteriorates (Ekama *et al.*, 1983).

Hydrogen-ion concentration is also one of the environmental factors affecting nitrification. Nitrification rates decline significantly at pH values below 6.8. The optimal pH values for nitrification range from 7.5 to 8.0. A pH of 7.0 to 7.2 is practically used to maintain reasonable nitrification rates (Metcalf & Eddy, Inc, 2003). Other environmental

factors to possibly inhibit nitrification may include toxicity, metals and un-ionized ammonia.

2.3.1.3 Biological Denitrification Process

Denitrification is a biological process, by which nitrate is reduced to nitric oxide, nitrous oxide, and nitrogen gas. In the absence of DO or under limited DO concentrations, nitrate or nitrite is used as an electron acceptor for the oxidation of a variety of organic or inorganic electron donors. The electron donors are the biodegradable soluble COD substrate either found in wastewater influent or produced internally from endogenous decay, the electron donors can also be an external source such as methanol or acetate or volatile fatty acid (VFA) produced from anaerobic fermentation within wastewater treatment.

The nitrate reduction reactions include a series of reduction steps from nitrate (NO_3^-) to nitrite (NO_2^-), to nitric oxide (NO), to nitrous oxide (N_2O), and to nitrogen gas (N_2). The overall heterotrophic denitrification reactions can be shown as following:

BOD in wastewater:

$$C_{10}H_{19}O_3N + 10NO_3^- \rightarrow 5N_2 + 10CO_2 + 3H_2O + NH_3 + 10\ OH^-$$

Methanol:

$$5CH_3OH + 6NO_3^- \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^-$$

Acetate:

$$5CH_3OOH + 8NO_3^- \rightarrow 4N_2 + 10CO_2 + 6H_2O + 8OH^-$$

3.57 g of alkalinity (as $CaCO_3$) is produced when 1 g of nitrate nitrogen is reduced. It equates 50% of the alkalinity destroyed by nitrification. No significant effect on the denitrification rate has been found for pH between 7 and 8. The oxygen equivalent of nitrate nitrogen is 2.86 g O_2/g NO_3^--N (Metcalf & Eddy, Inc, 2003).

Denitrifying bacteria are both heterotrophic and autotrophic. The heterotrophic organism genera include: *Achromobacter, Bacillus, Corynebacterium, Flavobacterium, Paracoccus, Pseudomonas, Rhizobium, and Methanomonas*. Among these genera, *Pseudomonas* species are found to be the most prevalent of all the denitrifiers and capable of consuming a wide range of organic compounds including hydrogen, methanol, carbohydrates, organic acids, alcohols, benzonates, and other aromatic compounds. Most of denitrifying heterotrophic bacteria are facultative and are able to use oxygen as well as nitrate or nitrite and even carry out fermentation in the absence of nitrate or oxygen. Other autotrophic bacteria can use hydrogen and reduced sulfur compounds as electron donors for defnitrification. Some heterotrophic bacteria, such as *Paracoccus pantotropha*, were reported to have the ability of simultaneous nitrification and denitrification under aerobic conditions. Some autotrophic nitrifying bacteria, such as *Nitrosomonas europaea*, are able to oxidize ammonia by using nitrite as electron donors with the process to convert ammonia to nitrogen gas (Metcalf & Eddy, Inc, 2003).

Biological denitrification requires certain anoxic volume or time to complete the objective of total nitrogen removal for both NH_4-N oxidation and NO_3^--N and NO_2-N reduction to nitrogen gas. The anoxic reactor volumes used for anoxic / aerobic processes

range from 10 to 30 percent of the total volume (anoxic plus aerobic) for treating domestic wastewater. The sludge settle ability decreased quickly when the actual retention time within the anoxic zone was longer than 1 hour. This constrained the denitrification ability in the conventional sludge system. The denitrification capacity of an anoxic zone is defined as the ability to reduce the maximum nitrate. If the nitrate load is above the denitrification capacity, nitrate will exit from the system and be present in the effluent. If the nitrate load is no more than the denitrification capacity, the nitrate will be reduced to zero in the effluent. When an anoxic zone is fixed at certain volume configuration, more nitrate than the denitrification capacity will not be reduced by increasing the nitrified mixed liquor recirculations. In the BNR system, in order to have a high phosphorus reduction, nitrate must be reduced to zero or at least a minimum value before entering the anaerobic zone (Ekama *et al.*, 1983).

Four conditions are required for denitrification to occur: a) presences of nitrate; b) absence of dissolved oxygen; c) existing facultative anaerobes, which can utilize nitrate and oxygen as terminal electron acceptors and be able to adapt to both aerobic and anoxic conditions. d) suitable electron donor or "energy source" such as readily biodegradable organic carbon (Heise, 2002). At a certain sludge age of a BNR process, the biological nutrient reduction efficiency is dependent on the ratios of TKN / COD and TP / COD in the influent. Complete denitrification can be achieved only when the TKN / COD ratio is below 0.08 mg N / mg COD. The nitrogen reduction efficiency may be reduced at the higher TKN / COD ratio above 0.08 mg N / mg COD. For a TKN/COD ratio above 0.14 mg N / mg COD, the biological phosphorus reduction efficiency may be reduced due to

incomplete denitrification resulting in nitrate discharge to anaerobic zone in a BNR system (Ekama *et al.*, 1983). Bertanza (1997) reported that a high total nitrogen reduction of 90% was achieved by a simultaneous nitrification-denitrification process.

2.3.2 Biological Phosphorus Removal

Biological phosphorus removal is the removal of phosphorus by incorporation into biological cells. The application of biological phosphorus removal has been widely encouraged since the early 1980s when the full-scale plant for biological phosphorus removal was successfully operated. Chemical-physical removal of phosphorus from wastewater is only practical with the orthophosphate form. The advantages of reduced chemical costs and less sludge production outperformed the chemical precipitation using alum or iron salts for phosphorus removal.

2.3.2.1 Forms of Phosphorus

The common forms of phosphorus in wastewater are orthophosphate, polyphosphate, and organic phosphate. The orthophosphates include PO_4^{3-}, $H_2PO_4^-$, H_3PO_4, which are readily available for biological metabolism. The polyphosphates contain two or more phosphorus atoms as well as oxygen atoms, and hydrogen atoms. Polyphosphates hydrolyze to the orthophosphate forms in aqueous solutions through a slow hydrolysis process. The organic phosphate is usually of minor importance in domestic wastewaters, compared to its importance in industrial wastes and wastewater sludges.

2.3.2.2 Sources of Phosphorus

The phosphorus load to surface waters mainly originates from natural conditions, such as surface runoff, precipitation, groundwater, bottom sediments and decaying plant or animal material, and from human activities, such as discharge of wastewater, industrial and agricultural sources (Baetens, 2001).

2.3.2.3 Biological Phosphorus Removal Process

The phosphorus is removed from wastewater by incorporation into cell biomass and then wasting out the sludge. The biological phosphorus removal process can be described as a twofold process: (1) In an anaerobic phase whereas no existence of either oxygen or molecularly bound oxygen, cell internal polyphosphate chains are hydrolysed to orthophosphates, a process which delivers the necessary energy for the polyphosphate accumulating organisms (PAOs) to store internal storage polymers as poly-β-hydroxybutyrate (PHB); (2) In the following anoxic or aerobic phase the stored PHB is metabolized providing energy from PHB oxidation and carbon for cell growth (Baetens, 2001). In the anoxic zone, nitrate can be utilized as an electron acceptor by a large fraction of the PAOs for the simultaneous oxidation of the stored PHB and uptake of phosphorus (Barker and Dold 1996). The polyphosphate bonds are formed in cell storage when the bacteria uptake excess soluble orthophosphate ($O\text{-}PO_4^{3-}$) from the wastewater. The stored phosphorus is ultimately removed from the bioreactor as a portion of the biomass wasted. However, lack of easily biodegradable organics in the influent may lead to the low efficiency of biological phosphorus removal. Stephens and Stensel (1998) reported that in an anaerobic / aerobic sequencing batch reactor, only 40 % to 60% of the

released phosphorus in anaerobic zone was taken up in the subsequent aeration zone under acetate-deficient conditions.

In a combined BNR process, a biological denitrification process is incorporated to prevent excessive amounts of nitrate from entering the anaerobic zone by the returned activated sludge (RAS) recycle. If only less easily biodegradable organics are available for phosphorus-storing bacteria, the efficiency of biological phosphorus removal will be reduced, because heterotrophic bacteria (denitrifiers) will use nitrate to consume rbCOD in the anaerobic zone, and out-compete Bio-P bacteria for VFA, resulting in dentirification.

The organisms responsible for biological phosphorus removal are mostly defined as polyphosphate-accumulating organisms (PAOs) or biological phosphorus removing organisms (Bio-P). The key characteristics of these organisms are acetate uptake, storage of PHB and release of ortho-phosphate under anaerobic conditions and consumption of stored PHB, uptaking $O\text{-}PO_4^{3-}$ and conversion of poly-P for storage under the subsequent anoxic or aerobic conditions (Baetens, 2001). There are three major types of PAOs: (1) the PAO only capable of using oxygen; (2) the facultative PAO capable of utilizing both nitrate and oxygen; (3) the PAO only able to use nitrate as the electron acceptor (Ahn *et al.*, 2002). However, the growth rate of PAOs under anoxic condition is lower than that of PAOs under aerobic condition. Hu *et al.* (2002) indicated that anoxic PAO growth rate was about 70% of aerobic PAO growth rate. The stoichiometric coefficient for anoxic phosphorus uptake per PHB COD utilized was about 80% of aerobic phosphorus uptake.

The readily biodegradable COD was used less efficiently by anoxic PAOs as compared to aerobic PAOs. The typical phosphorus composition of common heterotrophic bacteria ranges from 1.5 to 2.0 percent. But many other bacteria can store phosphorus in the form of energy-rich polyphosphates in their cells up to 20 to 30 percent by dry weight. In the anaerobic zone, concentrations of $O\text{-}PO_4^{3-}$ can be found in literature as high as 40 mg/L, compare to wastewater influent concentrations of 5 to 8 mg/L. The orthophosphate uptake in the aerobic zone is proportional to the orthophosphate release in the anaerobic zone. The orthophosphate uptake rate is not largely dependant on the sludge age of the system. The PAOs may maintain great survival ability and live at a very low endogenous mass loss rate (Wentzel *et al.*, 1988).

The efficiency of biological phosphorus removal largely depends on feed characteristics, temperature and operational conditions. Factors that influence Bio-P removal include the presence of oxygen, nitrite, and nitrate in returned sludge, pH, excess volatile fatty acid (VFA), temperature and easily biodegradable carbon in the influent. The recent research indicated that the presence of nitrite inhibits both aerobic and anoxic phosphate uptake, and the phosphate uptake was more affected under aerobic condition than that of anoxic condition (Saito *et al.*, 2004). When pH is around 7.0, pH in anaerobic zone may not be affected by the biological phosphorus release. But the uptake of orthophosphate increases the pH of the mixed liquor along aerobic zones. High pH may upset the biophosphorus removal system (Wentzel *et al.*, 1988). Baetens (2001) reported that the aerobic phosphorus uptake rate showed a maximum in the range of 15 to 20 °C. Bio-P removal efficiency will be reduced at pH values below 6.5. System performance is not affected by

DO when the aerobic zone DO concentration is kept above 1.0 mg/L. Barnard (1983) indicated a practical method to monitor the sufficiency of aeration by observing the ammonia residue in the effluent. Sufficient aeration for the reduction of both phosphorus and nitrogen should be ensure when the ammonia concentration in the effluent is just below 1 mg/L. Excessive aeration may lead to insufficient denitrification due to DO being returned to anoxic zone. The undenitrifiifed nitrates may in return upset the anaerobic conditions to reduce the phosphorus reduction efficiency. Due to the importance of acetate uptake for the growth of PAOs in anaerobic zone, the significant amounts of dissolved oxygen or nitrate entering the anaerobic zone will deplete acetate and hinder the treatment performance. The amount of dissolved oxygen and nitrate in the return sludge flow to the anaerobic zone should be minimized. Since most of the biodegradable soluble COD (bsCOD) can be converted to acetate in anaerobic zone, the amount of bsCOD available in the wastewater influent becomes very important for biological phosphorus removal. If the easily biodegradable organics concentration in the influent is below 60 mg/L, the phosphorus reduction is unlikely to be obtained. If bsCOD is no less than 60 mg/L, the phosphorus reduction can be obtained provided nitrate can be reduced to zero or minimum before the anaerobic zone. The high total COD leads to high easily biodegradable organics in the influent. The higher bsCOD, the easier it is to establish the conditions for a good phosphorus reduction. High biological phosphorus and nitrogen reduction require low TKN / COD and TP / COD ratios, high COD strengths and easily biodegradable COD fractions (Ekama *et al.*, 1983). About 10 g of bsCOD is required for every one gram of phosphorus removal by biological means. Sufficient bsCOD or VFA lead to the better performance for biological phosphorus removal

systems. Barnard (1983) reported that there was little difficulty in nitrate and phosphate reduction when the COD / TKN ratio was at 10 : 1 and above.

The anaerobic nominal HRT is closely related to the available P ratio of the available substrate in the anaerobic zone. When the TCOD: TP ratio varied from 42 to 68 (that is, phosphorus-limiting conditions), the performance of biological phosphorus removal is seldom affected by a change in anaerobic HRT. However, when the TCOD : TP ratio is between 20 and 43 (that is, COD-limiting conditions), changes in anaerobic HRT between 0.5 and 2.7 hours has large effects on Bio-P removal performance. TCOD:TP ratio in the process influent also influences the temperature effects on Bio-P removal process. Temperature has a stronger effect on the system when COD is limiting than when phosphorus is limiting (WEF, 1998).

Adam *et al.* (2002) reported that higher biological phosphorus removal was obtained under similar operation conditions of solid retention time and mass organic loading, as compared to conventional BNR activated sludge system. TP and PO_4^{3-}-P concentrations in the effluent were lower than 0.2 and 0.1 mg/L, respectively. Gnirss *et al.* (2002) indicated that the orthophosphate uptake mainly occurred in the anoxic zone. The biological phosphorus removal reached up to 20 to 25 mg/L with phosphorus spiking.

2.4 Solid Retention Time

Solid retention time (SRT) represents the average time during which the activated-sludge solids are retained in the bioreactor. For a combined BNR-MBR system, the SRT is

defined by dividing the mass of solids in the membrane bioreactor by the sludge wasting rate from the system. The equation 1 indicates the relationship between SRT, reactor volume, average concentration of mixed liquor suspended solids (MLSS), wasted sludge concentration and waste sludge rate:

Equation 1

$SRT = V * X_{ave} / Q_w * X_w$

Where: SRT = mean cell residence time, day

V = MBR volume, L^3

X_{ave} = the average MLSS concentration in MBR, kg/L^3

Q_w = the wasted sludge flow rate, $L^3\ day^{-1}$

X_w = the concentration of wasted sludge, kg/L^3

SRT is one of most critical parameters for the design and operation of an activated-sludge system. SRT affects the treatment process performance, aeration tank volume, sludge production, and oxygen requirements. Because of the slow growth of the bacteria responsible for nitrification, systems designed for nitrification generally have much longer hydraulic and solids retention times than those for systems designed only for BOD and biological phosphorus removal. Biological nutrient removal systems with longer SRTs are less efficient for biological phosphorus removal than shorter SRT designs due to the potential for a secondary release of phosphorus. The short SRT is preferred to achieve a good phosphorus reduction at a sacrifice of some nitrogen reduction. Good phosphorus or nitrogen reduction can balance each other depending on which nutrient need to be reduced critically (Ekama *et al.*, 1983). With extended SRT, the microbial

behaviour of high concentrations of biomass also changed. The sludge growth kinetic parameters, sludge yield and endogenous decay coefficients all decreased (Huang and Gui, 2001).

The MLSS concentration in the system can be controlled by SRT. An increased SRT will directly lead to an increased MLSS. However, the increasing MLSS may result in poorer sludge settling at a secondary clarifier in conventional BNR system. But MBR is not constrained by sludge settling quality and is more flexible for the selection of SRT. SRT of 15 to 30 days is commonly reported for BNR-MBR systems.

Since minimum aerobic SRT for nitrification are higher than that for Bio-P removal due to the slow growth of nitrifying organisms, the SRT for nitrification is one of the controlling factors in determining the total SRT for a BNR system. However, the solids retention time for both phosphorus and nitrogen reduction should be longer than that only for nitrogen reduction, because SRT is required to reserve the sufficient time to establish the anaerobic condition and the denitrification condition (Ekama *et al.*, 1983).

Lesjean *et al.* (2002) reported the efficient P-removal was achieved with 15 and 26 d SRT for MBR biological nutrient removal. Solid retention time has a significant effect on biological phosphorus removal system. The capacity for the phosphorus reduction may be lost at a SRT below 2.9 days depending on temperature (Mamais and Jenkins, 1992). In an enhanced biological phosphate removal system, phosphorus in the effluent was

reported to increase from 0.4 to 3.1 mg/L as the solid retention time decreased from 3.1 to 1.5 days (Shao *et al.*, 1992).

2.5 Temperature Effects on The BNR Process

Temperature affects the kinetics of the biochemical reactions for both phosphorus and nitrogen removal. Both the nitrification and denitrification are temperature dependent (Barnard, 1974). Temperature is a critical consideration for nitrifying bacteria. Temperature less than 15 °C have a strong negative effect on the growth of nitrifying organisms. Lower temperature requires a longer SRT to achieve nitrification due to the slow growth of nitrifying organisms. The denitrification efficiency decreased when the temperature decreased (Ekama *et al.*, 1983). Increased P-release and /or P-uptake rates with increased temperatures are being reported in the literature at temperature ranging from 5 °C to 30 °C (Baetens, 2001). The optimum temperature for the maximum phosphorus removal ranged from 28 to 33 °C in an enhanced biological phosphorus removal system (Mamais and Jenkins, 1992). But Barnard (1983) indicated that the biological phosphorus reduction was not much affected by low temperature provided that the anaerobic conditions could be properly maintained. Ydstebo and Bilstad (2000) reported that in a BNR plant in Norway, the biological nutrient removal was achieved at low temperature of 6 to 8 °C with an average of 0.25 mg/L phosphorus and 5.3 to 9.6 mg/L nitrogen in the effluent.

2.6 BNR-CAS Bioreactor Configuration

2.6.1 Retrofit of Plug-flow CAS Systems to Combined BNR Systems

A variety of options for biological nutrient removal are available through the retrofit of existing activated-sludge processes. In the retrofit of conventional activated sludge (CAS) systems, the selection of a BNR process largely depend on specific site, existing processes and equipment, and treatment needs. Most conventional plug-flow activated sludge (CAS) reactors can be easily converted to combined BNR systems by establishing non-aeration zones in the aeration tank and rerouting or adding sludge recycle lines (Randall *et al.*, 1992). Many combined BNR configurations have been successfully designed and operated at full-scale. They all include the basic steps of anaerobic, anoxic zones followed by an aerobic zone.

Two basic BNR configurations are A^2/O^{TM} and UCT (University of Cape Town). In the A^2/O process (Figure 1), both anaerobic zone and anoxic zone are included and combined with an aerobic zone. The RAS recycle containing nitrate is directed to the anaerobic zone from the secondary clarifier. The mixed liquor (aerobic recycle) from the back-end of aerobic zone is directed to the head-end of anoxic zone.

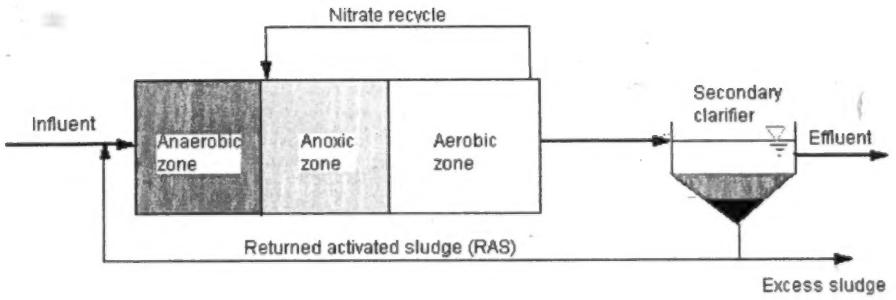

Figure 1. BNR configuration of A^2/O^{TM} process.

In the UCT process (Figure 2), the RAS recycle is directed to anoxic zone, and the mixed-liquor returned to the anaerobic zone is drawn from the end of the anoxic zone where the nitrate concentration is at minimum.

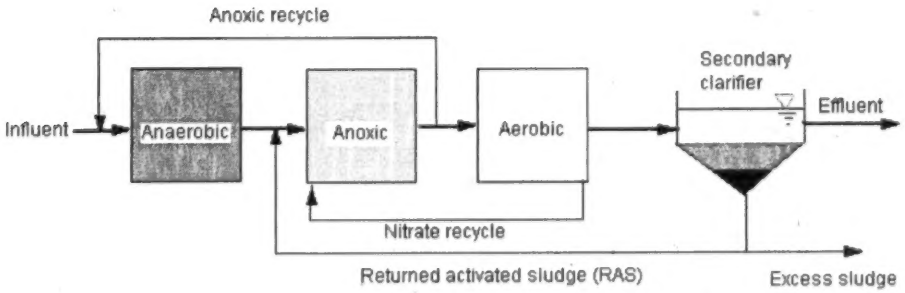

Figure 2. BNR configuration of UCT process.

The easily biodegradable organics (bsCOD) concentration in the anaerobic zone is dependent on the influent COD concentration, the bsCOD fraction and the mixed liquor recycle ratio (R1) to the anaerobic zone from the anoxic zone. The recycle ratio is typically equal to the influent flow rate (1:1). High ratio may probably lead to the high dilution of the bsCOD and ultimately results in low phosphorus reduction. Low R1 ratio may lead to less anaerobic biomass fractions and ultimately results in large anaerobic volume required to keep the same phosphorus efficiency (Ekama *et al.*, 1983). The UCT process is designed to treat relative weak wastewaters where the addition of nitrate would have a significant negative effect on the efficiency of the biological phosphorus removal. Some other BNR variations of A^2/O^{TM} and UCT include the Modified Bardenpho, Modified UCT, Virginia Initiative Plant (VIP), Johannesburg processes.

2.6.2 GBWWTP BNR Process

Originated from the Bardenpho process with the Johannesburg modification, GBWWTP BNR process (Figure 3) includes pre-anoxic, anaerobic, anoxic and aerobic zones in each bioreactor. Pre-anoxic zone is designed to reduce nitrate in the returned activated sludge (RAS) from the clarifier. Phosphorus release will be suppressed in anaerobic zone since heterotrophic bacteria will use the excessive nitrate as a terminal electron acceptor to consume rbCOD within this zone. By providing denitrification in pre-anoxic zone, nitrate contained in the returned activated sludge is thereby reduced, and the favorable condition for phosphorus release in the following anaerobic zone is maintained.

The mixed liquor recycle rate from the 4th path of aeration tank to anoxic zone typically ranges from 1 to 3Q. Thickened RAS recycle from the clarifier to pre-anoxic zone is typically at a rate of 0.75Q.

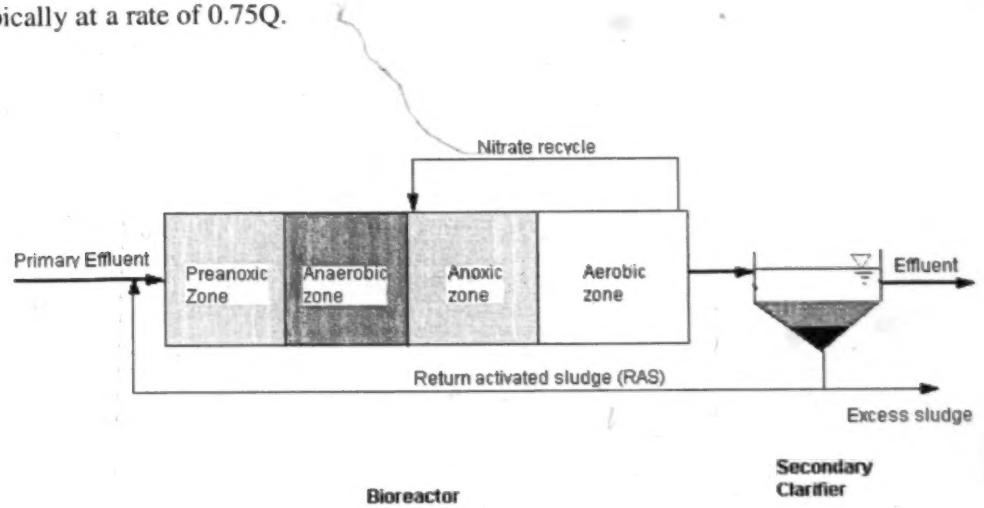

Figure 3. GBWWTP full-scale BNR process.

2.7 Limitations of BNR-CAS Process

2.7.1 Limiting Step of Secondary Clarification

The term BNR-CAS process stands for a BNR process adapted to a conventional activated sludge system (CAS). Similar to the CAS system, the ability of BNR-CAS process is limited by secondary clarification. Activated sludge of high MLSS concentration normally does not settle well in clarifier and ultimately lead to high TSS in final effluent. The BNR-CAS process is not able to treat wastewater under conditions of longer SRT or higher MLSS concentration. Bulking and foaming sludge are still of the problems that occur quite often in BNR-CAS system. Therefore, due to the limiting step

of secondary clarification, to maintain a good settling sludge is one of the top priorities in the plant operation.

2.7.2 Bulking and Foaming Sludge

The common problems of bulking and foaming sludge are due to the growth of filamentous bacteria. In filamentous growth, filaments of single-cell organisms formed by bacteria are attached each other, and the filaments normally extend out of the sludge floc. The filamentous sludge, in contrast to the preferred dense sludge floc with good settling properties, has a high ratio of floc surface area to mass, which leads to poor settling. A variety of factors, which can cause sludge bulking, include wastewater characteristics, design limitations and operation issues. Filamentous organisms are competitive under conditions of low dissolved oxygen (DO), low substrate (or low F/M). Two types of bacteria, *Nocardia and Microthrix parvicella*, are related to foaming in activated-sludge processes.

Pitt and Jenkins (1990) reported that 66% of surveyed U.S. activated sludge plants were affected by *Nocardia* foaming. The operation strategy to control the *Nocardia* foaming was to reduce the sludge age to less than 6 days. The hydrophobic cell surfaces of these bacteria are easily attached to air bubbles and stabilize the bubbles to cause foam. Both organisms can be found at high concentrations in the foam above the mixed liquor. In the BNR-CAS system, the control of bulking and foaming sludge is a critical challenge for the plant operation.

2.8 Applications of Membrane Technologies in Wastewater Treatment

Membrane biological reactors (MBRs), consisting of an activated-sludge bioreactor and solids separation by membranes, have been increasingly applied in wastewater treatment. MBR technology not only achieved the consistent effluent quality by physical means of membrane filtration, but also provided the great potential to achieve the optimum capacity of the activated sludge process without any constrains of sludge settling properties. Roest et *al* (2002) reported over 1,000 MBRs are presently in operation worldwide. About 98% of the systems integrate the membrane separation process with an aerobic bioreactor rather than to an anaerobic bioreactor. 55% of the systems have the membranes submerged in the bioreactor while the remainder keeps the membranes external to the biological process. The majority of MBR plants in operation are solely designed for the removal of organic matter. All the pilots were operated and optimized to achieve a set discharge criteria of TN < 10 mg/L and TP < 1 mg/L. The average MLSS concentration in the pilot installations ranged between 8 to 12 g/L.

2.8.1 Membranes

A membrane is a thin layer of material, functioning as a selective barrier, allows the passage of certain constituents and retains other constituents in the liquid. The constituents can be in states of gas, liquid or solid. Membrane processes are classified in a number of different methods including the type of material, driving force, separation mechanism, nominal size. Common membrane processes include microfiltration (MF),

ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), dialysis, and electrodialysis (ED). Table 4 indicates the general characteristics of membrane processes.

Table 4. Typical characteristics of membrane technologies for wastewater treatment.

Membrane process	Pore size	Typical operating range, µm	Rate of flux L/m^2-hr	Typical constituents removed
Microfiltration	Macropores (>50 nm)	0.08 to 2.0	17 to 68	TSS, turbidity, protozoan oocysts and cysts, some bacteria and viruses
Ultrafiltration	Mesopores (2 to 50 nm)	0.005 to 0.2	17 to 34	Macromolecules, colloids, most bacteria, some viruses, proteins
Nanofiltration	Micropores (<2 nm)	0.001 to 0.01	8.5 to 34	Small molecules, some harness, viruses
Reverse Osmosis	Dense (<2 nm)	0.0001 to 0.001	13.6 to 20	Very small molecules, color, hardness, sulfates, nitrate, sodium, other ions

Adapted from Metcalf & Eddy, Inc (2003).

Some of the most common terms used in membrane technology are permeate, concentrate or retentate, fouling, membrane element, module, transmembrane pressure (TMP), flux, dead-end filtration and crossflow filtration. Permeate is the portion of the feed that passes through the membrane. The concentrate or retentate is the portion of the feed that is rejected by the membrane. Fouling is the deposition of the rejected constituents on the feed side of membrane surface. Membrane element is a single membrane unit consisting of only membranes to provide a nominal surface area. Module is a complete set of the membranes, the support structure, the aeration tubing and all the connection ports.

The transmembrane pressure (TMP) is the pressure difference applied on both sides of membrane. TMP is used to monitor the condition of the membranes. As Figure 4 indicates, the simplified calculation for TMP can be expressed by equation 2.

Equation 2

$$TMP = PT + (Hp - Hw) / C$$

Where, TMP = Transmembrane pressure

PT = Measured pressure or applied vacuum (kPa)

Hp = Height of pressure transmitter (mm)

Hw = Water level (mm)

C = Conversion factor 102 (mm / kPa water)

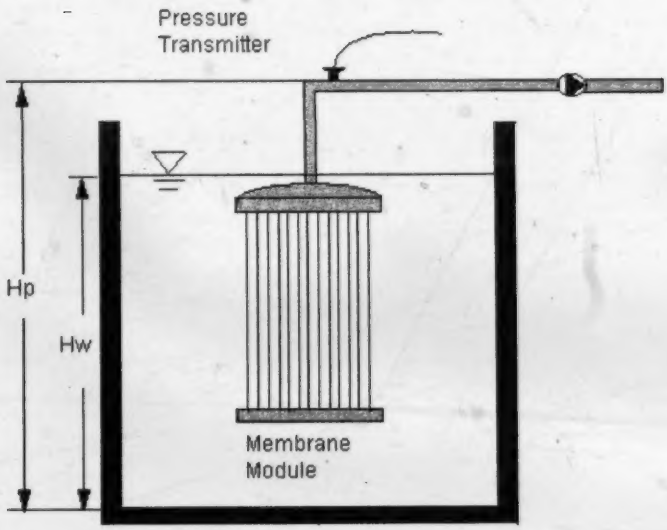

Figure 4. Membrane tank.

Flux is the mass or volume rate of permeate flow per unit of the membrane surface area. It is a measurement of the hydraulic performance of a membrane module. In steady-state conditions, the flux can be expressed by Equation 3.

Equation 3

$J_p = Q_p / A_m$

Where, J_p = flux, (Litres / m^2 / s) or (m^3 / m^2 / s)

Q_p = permeate flow rate (L/s)

A_m = membrane area (m^2)

The typical flux operating range of hollow fibre membrane for wastewater treatment is 17 to 34 L / m^2-hr (Zenon Environmental Inc., 2004).

Filtration can be categorized into dead-end filtration and crossflow separation. In dead-end filtration, the fluid flow is perpendicular to the membrane surface. The rejected constituents remain on the membrane surface and contribute to the build-up of a cake layer, which leads to a declining permeate flow. The periodic backwash is therefore required to remove the cake layer and recover the membrane flux. Dead-end filtration is applied commonly in removing particles. In crossflow separation, the feed stream runs parallel to the membrane surface. Some fluid pass through the membrane under differential pressure, while the remaining fluid, at applied operating pressure, produces the shear forces of the turbulent flow over the membrane surface to limit the formation of cake layer. The permeate productivity is greatly increased, compared to the dead-end filtration. However, energy demand is also higher for crossflow filtration (Gunder, 2001).

2.8.2 Membrane Bioreactors

Membrane bioreactor systems have two basic configurations: One is the submerged MBR (Figure 5), which keeps membranes immersed in the bioreactor, and the other is the recirculated MBR (Figure 6), in which an external membrane separation unit is placed outside the bioreactor.

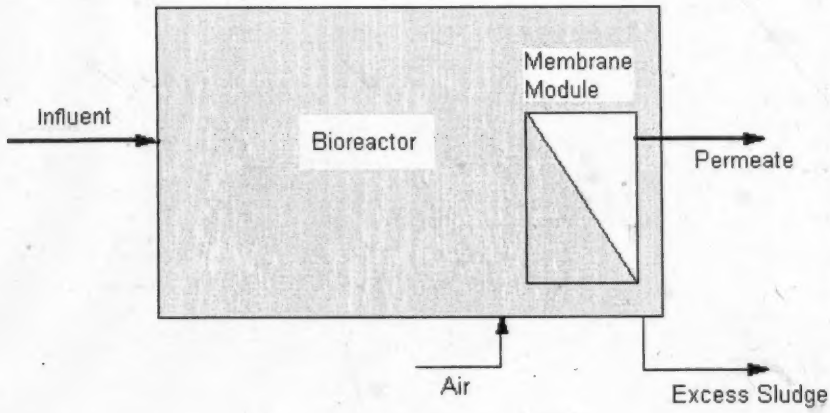

Figure 5. Schematic representation of submerged MBR.

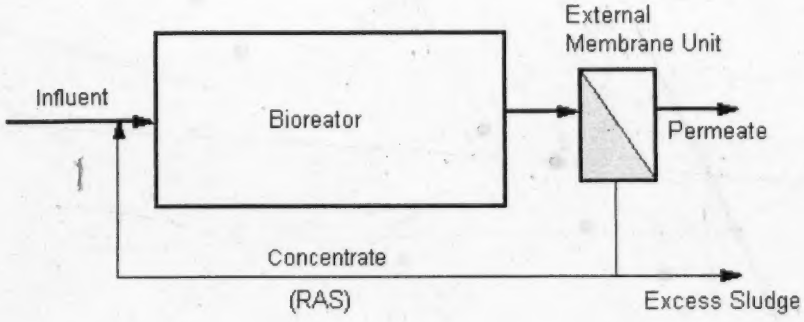

Figure 6. Schematic representation of recirculated MBR.

By eliminating secondary clarification and operating at higher MLSS concentration, MBR provides a number advantages: (1) higher loading and shorter HRT; (2) longer

SRTs resulting in less sludge production; (3) low DO with potential for simultaneous nitrification and denitrification in long SRT designs; (4) high-quality effluent in terms of low turbidity, bacteria, TSS, and BOD; (5) less space required for wastewater treatment. Disadvantages may include high capital costs, limited data on membrane life, potential high cost of periodic membrane replacement, higher energy consumption, and the operation requirement to control membrane fouling.

In the MBR system, MLSS concentration of the aeration tank is no longer of concern for secondary solids loading limitations. It can be as high as 25,000 mg/L. It is also reported that MLSS concentrations ranging from 8,000 to 10,000 mg/L are most cost effective with considerations of all factors. Witzig *et al.* (2002) reported that the MLSS was maintained between 20000 to 60000 mg/L due to the complete biomass retention for an aerobic MBR treating municipal wastewater over a period of 380 days. Because of the limiting substrate condition in the highly concentrated mixed liquor, the bacteria was only able to keep their maintenance metabolism through any available carbon sources and were not in a physiological state of any growth. This explained a zero net biomass production occurred in the MBR. Hasar and Kinaci (2002) also reported that with high concentration of MLSS, the viability of biomass in the bioreactor was significantly reduced due to the accumulation of inert compounds and the reducing activities of poor biomass.

For the study of biological nutrient removal combined with membrane technology for municipal wastewater treatment, Adam *et al.* (2002) reported high performances of

enhanced biological phosphorus removal process in MBR technology. The effluent P-concentrations were lower than 0.2 mg TP/L. An MBR bench-scale plant (210 L) was operated in parallel to a conventional wastewater treatment plant under comparable process conditions. The influent total phosphorus concentration ranged between 8 and 15 mg/L. Effluent P-values were very low and stable between 0.05 to 0.16 mg/L for total P and 0.04 to 0.1 mg/L for ortho-phosphate (99% of the values). Rosenberger *et al.* (2002) also reported a 95% COD reduction, a complete ammonia nitrogen reduction and over 82% of total nitrogen reduction over a 535-day study period for a municipal wastewater treatment in a MBR. Ujang and Salim (2002) indicated that in an intermittent aeration membrane bioreactor, the reduction efficiencies reached 98% for COD, 96% for nitrogen and 78% for phosphorus. In a two stage intermittent aeration MBR system, total nitrogen reduction reached 91.6% and total phosphorus reduction, in the meantime, achieved 66% with high organic reductions of 98% BOD and 96.2% COD (Seo *et al.*, 2000). Ahn *et al.* (2003) reported that in a 10 L bench-scale test using intermittent recycles for alternating anoxic/anaerobic conditions, total phosphorus reduction reached 93% and total nitrogen reduction reached 60% with a SRT of 70 days and HRT of 8 hours, where the Kubota flat-sheet membrane (0.4 μm) was used.

2.8.3 Membrane Fouling

Membrane fouling presents the most difficult challenge to the design and operation of membrane systems. Fouling leads to loss of permeate productivity and loss of permeate quality. All membrane systems are inevitably facing the fouling problems due to the nature of membrane operation. No unified and well structured theories on membrane

fouling are currently available because of the complexity of the biomass matrix (Chang *et al.*, 2002). Generally, fouling of membrane can occur in three forms: (1) depositions of rejected constituent on the membrane surface, (2) scaling or chemical precipitation, and (3) chemical or biological damages to the membrane, such as acids, bases and bacteria (Metcalf & Eddy, Inc, 2003). Common problems associated with membrane fouling are increased operational transmembrane pressure, increased energy consumption and reduced membrane life (Zenon Environmental Inc., 2004). Three common methods are used to control membrane fouling, which are feed pretreatment, membrane backflushing and chemical cleaning. The most widely applied method of membrane fouling control is backflushing with either permeate and/or air. Chemical treatment is used to remove the residue depositions left after conventional backflushing. Another method reported for membrane cleaning is using electric pulses known to be electrophoretic membrane cleaning. The method was successful in a bench scale test for microfiltration and ultrafiltration processes by reducing membrane fouling at different variables (Ibrahim and Bowen, 2002).

One of the most common operation problems for BNR-MBR is membrane biofouling, which is the main cause of permeate flux decline and loss of product quality. Biofouling leads to considerable technical problems and economic loss. Not only biofouling on the feed side of the membranes is concerned but microorganisms may also pass the membrane, although it is believed that microorganisms are too large to penetrate a reverse osmosis membrane. No technology is currently available to take biofilm samples non-destructively from an operating membrane. The far most widespread approach

against acute biofouling problems is the application of biocides. The conventional anti-fouling strategy is to dose continuously with biocides. A rational anti-fouling strategy should reflect the properties and dynamics of biofilms (Flemming, 2000). The previous BNR-MBR study (Heise, 2002) indicated the microorganism contamination in permeate side of membrane module but not much fouling in feed side during the study period. It was probably due to very low permeate flux and relaxation operation mode. However, the measures should be taken to ensure the integrity of membrane module. Hong and Bae (2002) indicated that the mixed liquor suspended solids (MLSS) concentrations had very little influence on permeate flux in the range of 3600 to 8400 mg/L. Non-continuous membrane operation significantly reduced membrane fouling by diffusing away the deposits attached to the membrane surface. The operational parameters also had influence on membrane fouling, such as aeration intensity, membrane flux, transmembrane pressure (TMP). Gui and Huang (2003) observed that there was a critical membrane flux over which membrane fouling increased with a sharp increase of TMP. The study suggested that in order to obtain a long-term stable operation, a membrane bioreactor should be operated in the flux range where no obvious sludge deposit or membrane fouling increased on membrane surfaces.

Besides coarse bubble aeration and backflushing, a maintenance cleaning method can also be applied to control membrane fouling. A solution of 100 mg/L sodium hypochlorite or citric acid can be used three times per week in the backwash mode for 45 minutes with subsequent 15 minute permeate flushing and 10 to 15 minute system purging (Zenon Environmental Inc., 2004).

3 Methods and Materials

Based on the previous study, two new 118 L bench-scale MBR bioreactors with more improved plug flow pattern were designed and constructed. GBWWTP process and UCT process were adapted for MBR1 and MBR2, respectively. Both MBRs were operated at HRTs of 4, 6 and 8 hours and a SRT of 15 to 20 days. The experiment operation was planned for 3 to 4 months, depending on the performance of BNR-MBR bioreactors.

3.1 Experimental Design

3.1.1 BNR-MBR Bioreactor

The design of bench-scale bioreactor was trying to emulate plug flow since the plug-flow recycle system is theoretically more efficient in the stabilization of most soluble wastes than in the continuous-flow stirred-tank reactor (CFSTR) system. However, in actual practice, a true plug-flow regime is essentially impossible to obtain because of longitudinal dispersion caused by aeration and mixing. By dividing the membrane bioreactor into a series of cells, the process approaches plug-flow kinetics with improved treatment efficiency compared to a complete-mix process.

In this experiment, each of BNR-MBR bioreactors consisted of 24 cells and was divided into three sections: non-aeration zones (NA), aeration zones (AO) and membrane tank (MT). Non-aeration zones include pre-anoxic zone (PR), anaerobic zone (AE), anoxic zone (AN). NA and AO zones were integrated into a series of cells with opening of

bottom and top of baffle wall, which maximize the flow length. Membrane tank was comprised of two cells, one was membrane cell, where the ZeeWeed® membrane module was situated, and the other was the feed cell, where primary effluent was maintained at a certain level to keep a continuous gravity flow to the bioreactors. The membrane cell was connected to the last cell (No.24) of AO zone by a 100 mm, 12.7 mm polyethylene tube. ZW-10 membrane modules were submerged into the membrane cell, which also served as the last aeration cell. This design provided the maximum plug-flow operation in both BNR-MBR systems.

In the BNR-MBR systems, phosphorus is only removed through the ultimate sludge wasting process. Therefore, considerations were given to an effective method of wasting excessive sludge. Since the clarifier separation in conventional treatment was replaced by membrane separation in MBR process, the sludge settling was an alternative consideration in the design of membrane bioreactors. In addition, the sludge recycled to the preanoxic zone and the anoxic zone from aeration zone must maintain very low level of DO (<0.2 mg/L). Therefore a small settling cell (R-cell), which was functioning in recycling sludge and wasting sludge, was designed and constructed within the membrane tank.

The new 118 L MBR bioreactor was divided into two units: bioreactor (86.4 L), which included NA zones and AO zones, and membrane tank (32 L). Bioreactor consisted of 24 cells; each cell was about 3.6 litres. The volumes described above and following were effective volume. The volume ratio of both MBRs is listed in Table 5.

Table 5. Volume ratio of different zones for both MBRs.

Zones	No. of cells	Zone Volume (L)	Volume ratio of zones
MBR1			
PR	2	7.2	6.1%
AE	4	14.4	12.1%
AN	6	21.6	18.2%
AO	12	43.2	36.5%
MT		32	27.0%
AO+MT		75.2	63.5%
MBR2			
AE	4	14.4	12.2%
AN	8	28.8	24.3%
AO	12	43.2	36.5%
MT		32	27.0%
AO+MT		75.2	63.5%

Plan and profile views of the BNR-MBR bioreactor are showed in Figures 7 and 8.

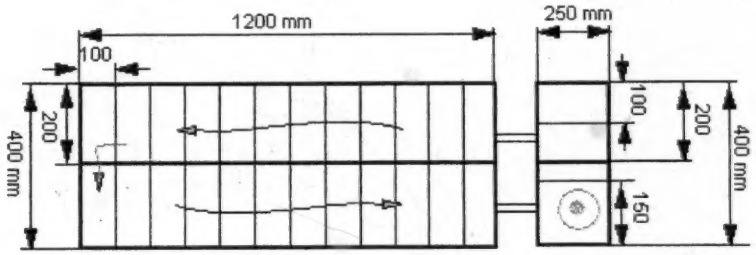

Figure 7. Plan view of BNR-MBR bioreactor.

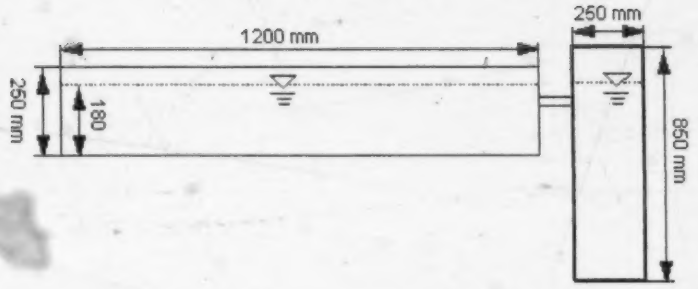

Figure 8. Profile view of BNR-MBR bioreactor.

The MBR bioreactors were constructed of plexi-glass material. The membrane unit of each reactor was designed to accommodate the 692 mm tall and 109 mm wide ZW-10 membrane element, with a 70 mm freeboard. The feed tank with a PE overflow cell was attached to the membrane unit in order to ensure a consistent primary effluent (PE) flow. One baffle plate was placed into membrane tank to separate a small settling unit (R-cell) with the following functions: a) minimizing dissolved oxygen from aeration; b) thickening sludge before it is recycled and/or wasted; and c) reducing the malfunction of level float caused by aeration turbulence. The 3D view of BNR-MBR bioreactor is illustrated in Figure 9.

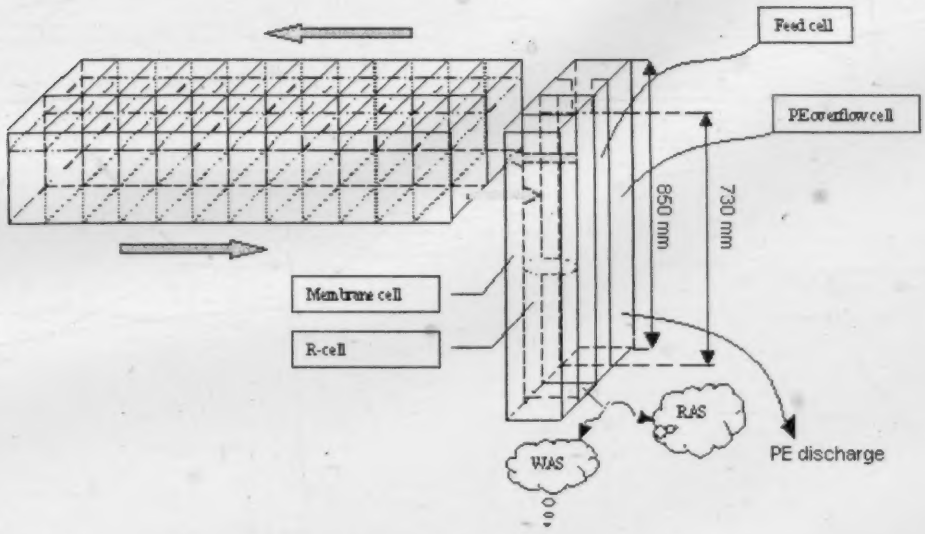

Figure 9. Three dimensional depiction of BNR-MBR bioreactor.

Two alternative BNR processes were selected to configure the BNR-MBR systems. MBR1 was to emulate GBWWTP process and MBR2 was adapted to UCT process. The process configurations are illustrated in Figure 10 and 11, respectively.

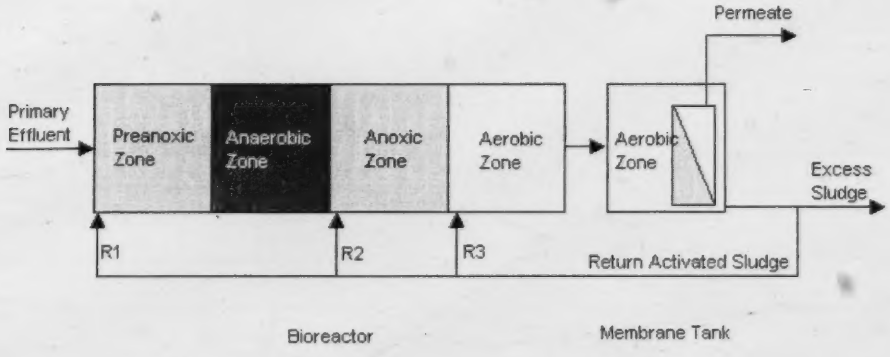

Figure 10. MBR1 configuration (GBWWTP process).

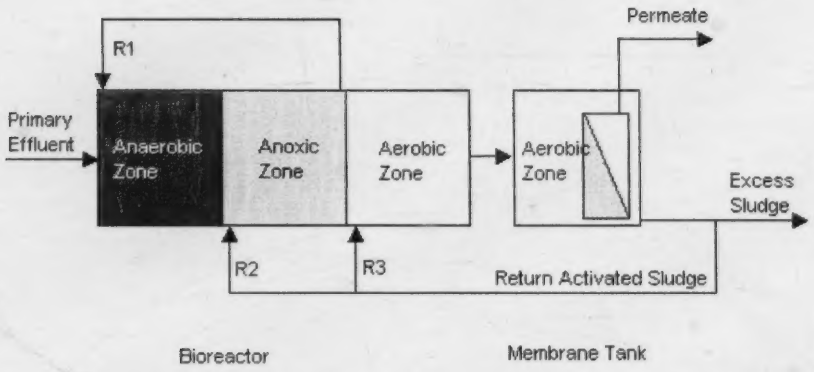

Figure 11. MBR2 configuration (UCT process).

3.1.2 ZW-10 Membrane Module

Three typical forms of membrane are currently available in commercial market for water and wastewater applications. They are flat sheets, fine hollow fibers and tubular form. They are mostly structured as a thin skin having a thickness of about 0.20 to 0.25 μm supported by a more porous structure of about 100 μm in thickness. The membranes for wastewater application are made of organic materials, which include polypropylene, cellulose acetate, aromatic polyamides, and thin-film composite (Metcalf & Eddy, Inc, 2003). There are many factors to be considered on the choice of membrane and system configuration for wastewater treatment. They may include treatment efficiency, flux capability, minimizing membrane fouling and deterioration, life span, cost for replacement, market availability. In this pilot-plant study, ZeeWeed® membrane of Zeon Environmental Inc. was selected. ZeeWeed® membranes are "outside-in" hollow fibre

membranes. The structure of a ZeedWeed® fibre (Figure 12) resembles a perforated straw. ZW-10 module (Figure 13) was used to configure the BNR-MBR systems for the wastewater treatment system.

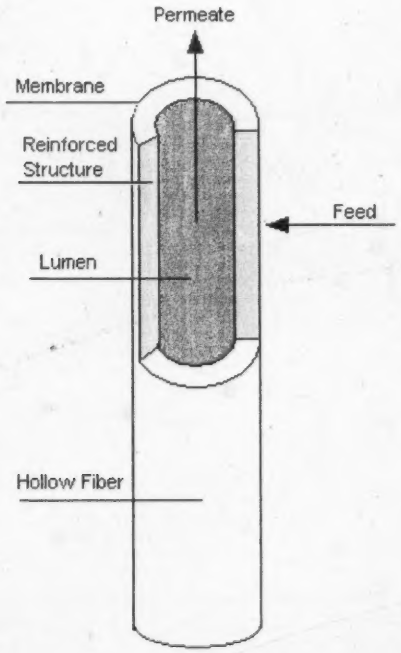

Figure 12. ZeeWeed® membrane fibres.

ZeeWeed® Membrane is a thin skin covered the outside surface of the fiber. Inside is an attached reinforced support layer of a more porous material. The membrane fibre is submerged in the feed water. A small vacuum (or ~35 kPa) is applied to the inside lumen of a membrane fiber by a permeate pump. The water is drawn through the outside surface of the membrane into the center lumen. The pores (0.04 μm) of the membrane function as physical barriers to stop unwanted constituents (Zenon Environmental Inc., 2004). The permeate flows along the lumen to the collection header and is pumped out.

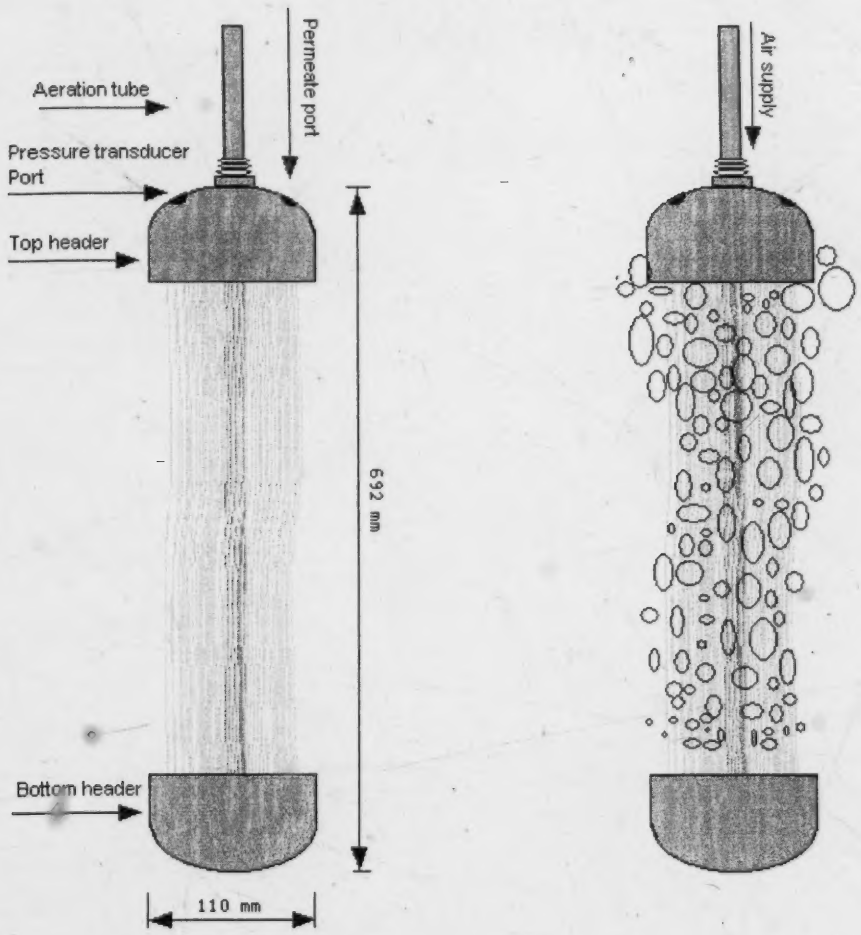

Figure 13. (a) ZW-10 membrane module. (b) Aeration bubble pattern.

In the membrane tank, a ZW-10 module comes with an extended aeration tube that is also used to attach the module to the support bracket to hold it in place vertically. The hollow fibres are lined up between the top header and bottom header. The permeate is drawn only from the top header. The bottom header is a dead end, where the fibres are embedded and sealed. The top header holds the open fibres with a sealed layer of resin. It has two holes on top header: one is for permeate connection and the other is for pressure

measurement. The permeate from each individual fibre is collected in the top header and pumped out. The center aeration tube suppliers air at 1.9 m^3/h through small holes near the bottom and top header where coarse bubbles are formed. The coarse bubble aeration provides scouring action to reduce the fouling of membrane surface, and in the meantime, also provides oxygen to the biomass and maintains mixing to the suspension. ZW-10 module specifications and operation conditions are listed in Table 6 and 7 (Zenon, 1999).

Table 6. Specifications of ZW-10 module.

Model	**ZW-10, Submersible Module**
Configuration	Outside/In Hollow Fiber
Nominal Membrane Surface Area	0.93 m^2
Nominal Pore Size	0.04 μm
Weight of Module (Drained)	1.9 kg
Weight of Module (Wet)	2.1 kg
Permeate (Fiber Side) Hold-up Volume	0.13 litres
Length * Width	692 mm * 110 mm

Table 7. ZW-10 operating conditions.

Maximum Transmembrane Pressure	62 kPa @ 40 °C
Typical Operating TMP	10 to 50 kPa @ 40 °C
Maximum Operating Temperature	40 °C
Operating pH range	5 to 9
Cleaning pH range	2 to 10.5
Maximum OCl^- Exposure	1000 mg/L
Maximum TMP Back Wash Pressure	55 kPa
Maximum Aeration Flow per Module	3.6 m^3/h

From ZeeWeed-10 Manual, 1999

3.2 Equipment Design and Setup

From the experience of the previous experiment set-up by Geoff Heise, the new pilot plant systems were designed and constructed in a way to overcome the shortcomings and difficulties occurred in the previous experiment. The new design and setup proved very effective during the 92 day period of the BNR-MBR pilot plant operation. Figure 14 illustrates a conceptual representation of both pilot plants configurations. Photos of the experiment setup are provided in Appendix B. Two new bioreactors and membrane tanks were designed and constructed in a way to provide a more plug flow like pattern. A simplified overflow feed system worked effectively to keep a continuous gravity feed flow. A new design of the mixing shaft and impellers ensured the efficiency of the mixing system for all non-aeration cells. A new application of the bendable air diffusers provided sufficient dissolved oxygen to the activated sludge and also provided good mixing to the suspension in all aeration cells, as well as membrane tanks. The applications of new backwash systems proved very important for the operation of BNR-MBR at a high flux rate and high MLSS. The new design of the auto-sampling systems worked smoothly for the collection of the composite permeates with a sampling schedule designed according to the results of tracer tests. The arrangement of protection aluminum baffles provided very good splash protection for both bioreactors and membrane tanks. The new tubing systems gave flexibility for the mixed liquor recycles. The design of continuous sludge wasting systems proved very crucial for the performance of the new BNR-MBR pilot plants.

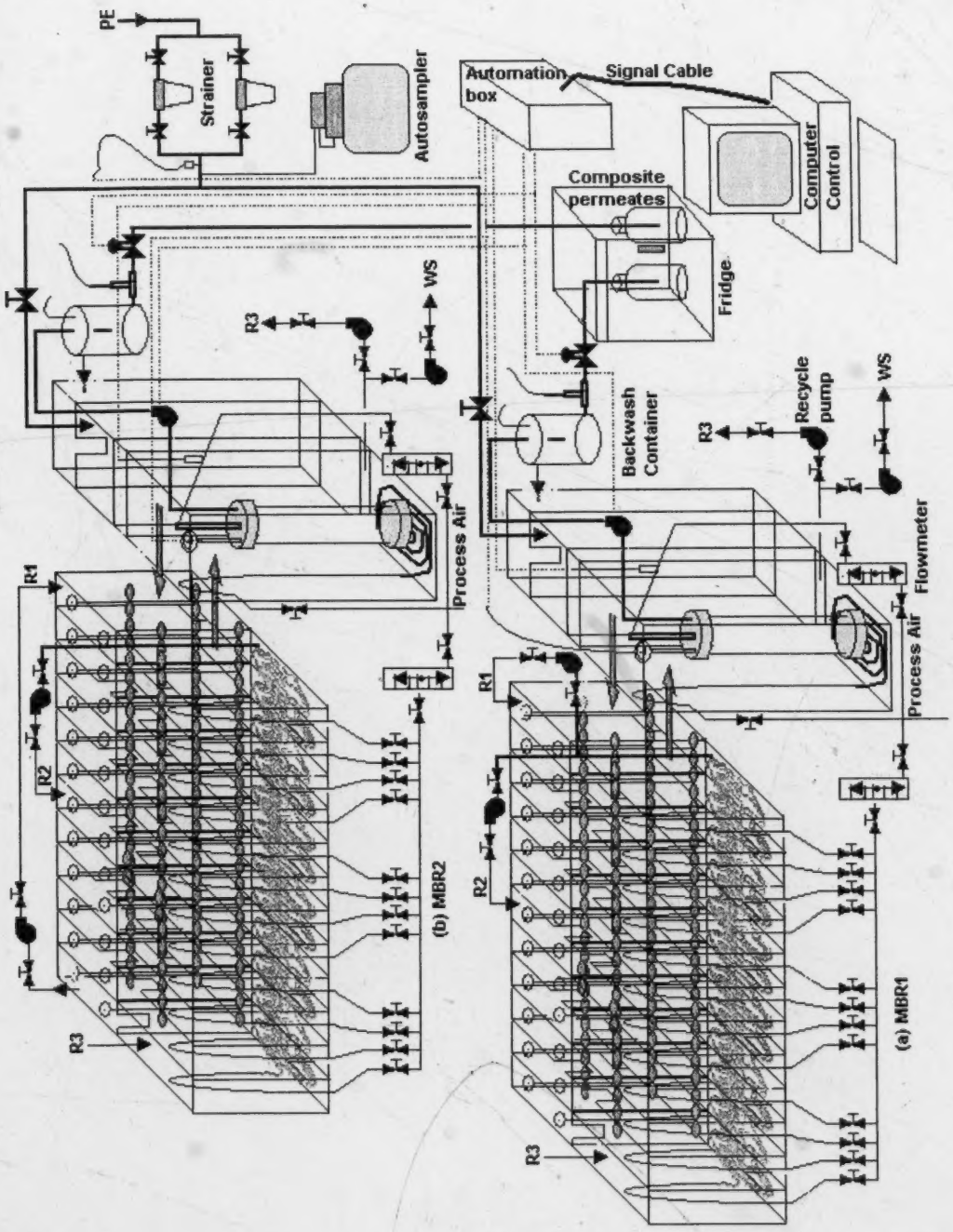

Figure 14. BNR-MBR pilot plant configurations.

3.2.1 MBR-Feed System

The pilot plant site located at GBWWTP No.5 sample gallery station below the secondary catwalk between the bioreactor and clarifier. The primary effluent feed for the two BNR-MBRs was taken from the PE feed channel of No. 1 bioreactor. A PE pipe line (25 mm) was installed and connected to the PE process line directly. A continuous primary effluent feed to both pilot plants was achieved by gravity flow. A screening unit (Figure 15) of two 900 micron mesh strainers was installed in the feed pipe prior to MBR PE units to prevent large debris from entering the MBR Feed systems.

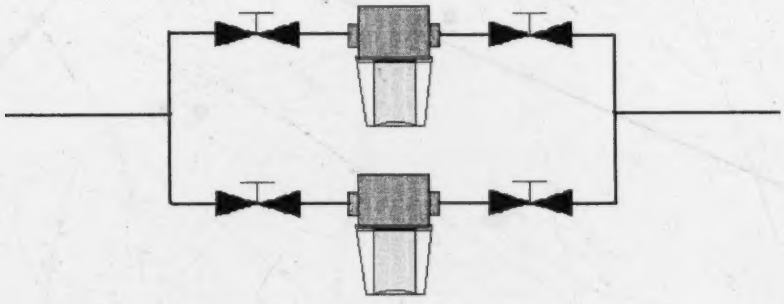

Figure 15. Screening unit.

One strainer was operated at a time. The other was the backup. The strainer was cleaned either daily or once every two days. Two strainer screening units ensured that the large material that could plug downstream equipment was removed and the PE flow continuously fed to the BNR-MBR pilot plants. This arrangement successfully prevented the BNR-MBR pilot plants from system plugging or potential damaging to the membrane fibres.

After screening unit, the primary effluent feed was distributed through a PVC manifold to the feed cells of both MBRs. The PVC manifold had four separate connections. One was housed by a temperature senser for temperature monitoring. The other was connected to a composite auto sampler to collect representative scheduled samples of the primary effluent entering the BNR-MBR systems. The other two connections were attached with two flexible 12.7 mm polyethylene lines which delivered screened primary effluent to the feed cells. Three stainless steel fittings were used to unite the connections, except for the PE autosample line, by a plastic push-to-connect fitting.

Each feed tank included two cells. One was feed cell and the other was overflow cell. Constant head in the feed cell was maintained with an about 73 mm high adjustable overflow weir near the top of the feed tank. The overflow was diverted into the overflow cell, where it was further discharged to the drain. The feed tank was attached to the membrane tank and the feed cell was connected to the No.1 cell of the bioreactor by a 100 mm flexible 12.7 mm polyethylene tube. Plastic push-to-connect fittings were used. A short flexible 12.7 mm polyethylene tube was also inserted in the other end of the push-to-connect fitting inside of the feed cell to prevent a backflow of the mixed liquor in bioreactor when the bioreactor was filled up with the mixed liquor prior to the start-up or when the feed cell needed cleaning. The setup of the feed distribution unit and the feed / membrane tanks are shown in Figure 16.

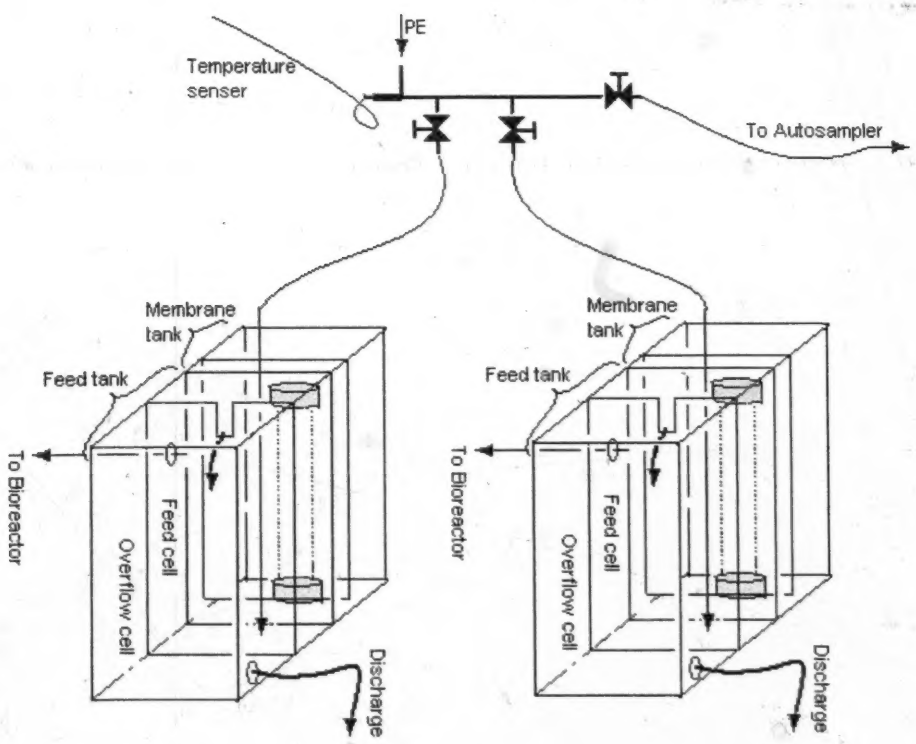

Figure 16. PE distribution manifold and feed / membrane tank.

3.2.2 Size of Integrated BNR-MBR Bioreactor

Two bioreactors and membrane tanks were made of plexi-glass. Bioreactors had already been constructed prior to the start of the thesis project. The dimensions of both bioreactors were about 1200 mm × 400 mm × 2500 mm. Both were constructed with a series of 24 cells. The dimension of each cell was about 100 mm × 200 mm × 250 mm. The theoretical volume of each bioreactor was about 120 L. The effective volume of each bioreactor was about 86.4 L (each cell was about 3.6 L). The design of the integrated BNR-MBR bioreactors was to emulate a plug flow pattern and enhance the biological

nutrient removal. The ratio of preanoxic: anaerobic: anoxic: aerobic zones for MBR1 was 1 to 2 to 3 to 10. The ratio of anaerobic: anoxic: aerobic zones for MBR2 was 2 to 4 to 10. In the previous study by Geoff Heise, the ratio of pre-anoxic: anaerobic: anoxic: aerobic zones was 1 to 2 to 1 to 12. The volume ratio of anoxic zone was increased from 1 to 3 in the new design to enhance the denitrification. The volume ratio of MBR1 was closer to that of the full-scale bioreactor at GBWWTP, in which the ratio of preanoxic: anaerobic: anoxic: aerobic was 1 to 1.2 to 3 to 16. The plan and profile views are shown in Figure 17 and 18.

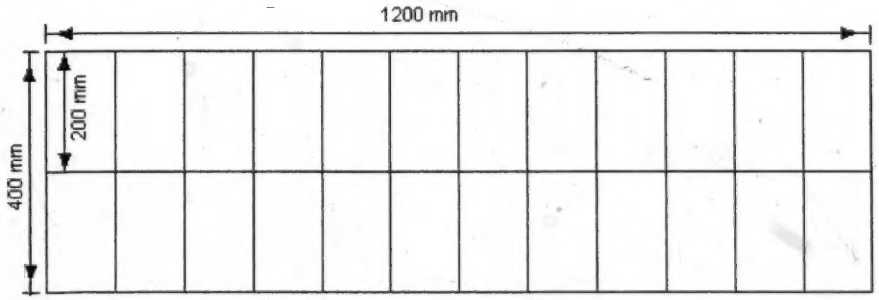

Figure 17. Plan view of the bioreactor.

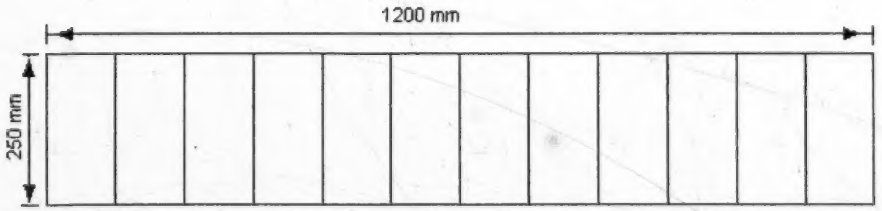

Figure 18. Profile view of the bioreactor.

In each cell, a square hole (25 mm × 25 mm) was cut at the outside bottom of one side wall and a rectangular opening (70 mm × 25 mm) were cut at the inside top of the other side wall. The opening design ensured a maximum flow length of each cell. Under the enhanced mixing, a series of 24 complete mixing cells together with a membrane tank was integrated into a plug flow bioreactor system, which provided solid ground for the performance of both BNR-MBRs. Figure 19 shows the three-dimension view of bioreactor cells and Figure 20 illustrates both aeration cell and non-aeration cell coupled with the air diffuser and mechanical mixing installation.

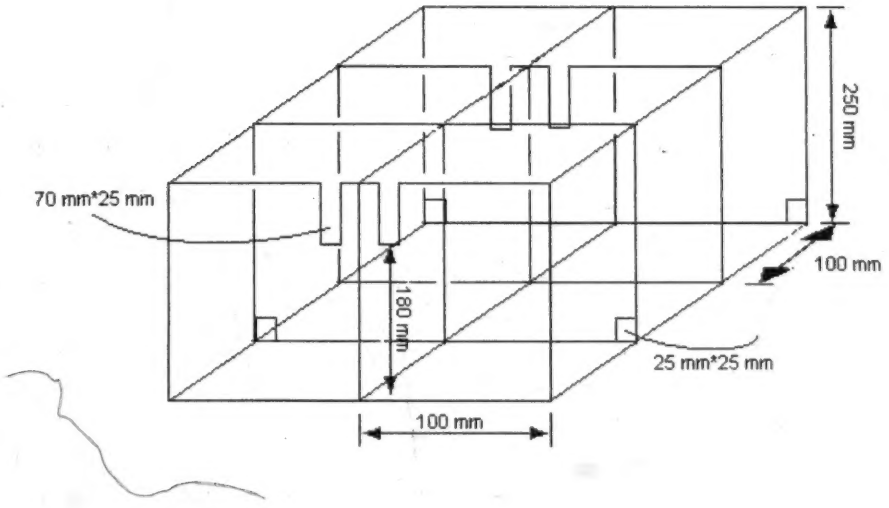

Figure 19. 3D view of bioreactor cells.

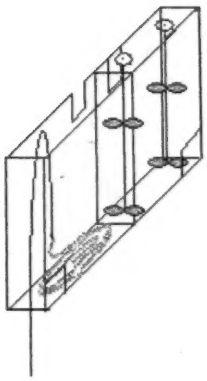

Figure 20. Illustration of air diffuser and mechanical mixing installations

The membrane tanks were designed to accommodate the ZW-10 module with 692 mm height and 110 mm width. The feed tanks were also integrated with the membrane tanks. Since the size of bioreactors was already fixed, the size of membrane tank was designed only to have sufficient space to hold the ZW-10 membrane module, and in the meantime the tank volume was minimized to reach a short hydraulic residence time (HRT) under a certain flux rate. The normal operation flux for ZeeWeed® membrane was recommended for 10.2 L/m^{2}h to 20.4 L/m^{2}h. The nominal surface area of ZW-10 was 0.93 m^2. The volume of the bioreactor was 86.4 L. Using the flux rate of 20.4 L/m^{2}h, without membrane tank added, the shortest HRT could be obtained by a 86.4 L bioreactor was 4.5 hours. A peak flux rate of 30 L/m^{2}h could produce a HRT of 3.1 hours. The shortest HRT in the experiment plan was 4 hours. Therefore the membrane tanks were designed and constructed with only consideration of a minimum volume to hold ZW-10 membrane module. The membrane tank was built in a dimension of 850 mm × 250 mm × 200 mm. The theoretical volume of the membrane tank was 42.5 L. The effective volume during

the operation was about 30 L to 32 L. The total effective volume of bioreactor and membrane tank was about 116 L to 118 L. Under this volume, the shortest HRT obtained at a peak flux rate of 30 L/m^{2}h was about 4 hours. Therefore the planned operation for a short HRT could be achieved. The attached feed tank was the same size with the membrane tank. The three-dimension view of membrane tank is illustrated in Figure 21.

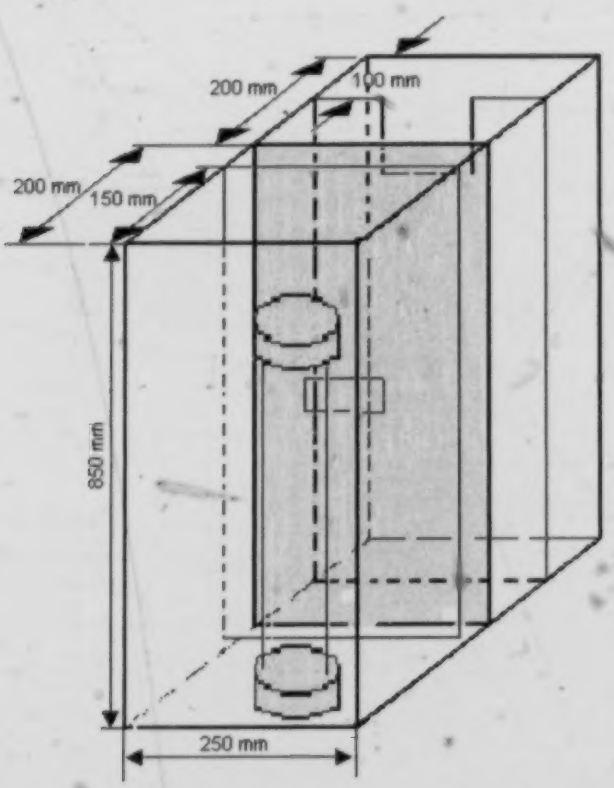

Figure 21. 3D view of membrane tank.

3.2.3 Backpulse Container

Since the experiment was planned to operate at high flux rate, the backpulse container was designed to support an efficient backpulse operation and to provide sufficient volume to hold permeate for autosample collection during the study. From the literature as well

as the recommendation of Zenon Environmental Inc., the ratio of production / backpulse was decided to use 15 min / 30 sec or 450 s / 15 s. Based on the requirements of backpulse and autosample collection, a 2 L backpulse column container was designed and constructed. Figure 22 illustrates the profile view of the backpulse container.

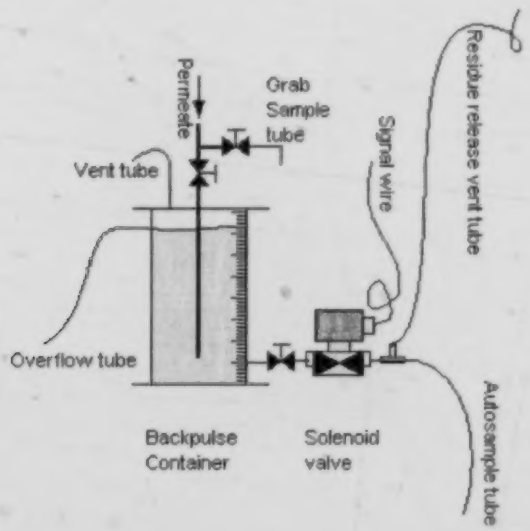

Figure 22. Profile view of the backpulse container.

A 9.5 mm polyethylene tube was inserted into the container. Permeate was delivered through this tube into container. A small hole was cut at top cover and a short 6.4 mm polyethylene tube was connected to the top of container. The tube was used as an air vent to prevent any vacuum in the container. The air vent tube always kept the container connected to the atmosphere and in the meantime minimized any possible contamination to the permeate samples. A 9.5 mm polyethylene tube was connected near the top of container to keep the permeate overflow discharge. A solenoid valve was connected near the bottom of container to take composite samples. A 6.4 mm plastic tee was placed right

after the solenoid valve and a 6.4 mm polyethylene tube was connected to the tee served as an air vent. It ensured that the sample residue was released by gravity flow to the sample bottle after the solenoid valve was closed.

3.2.4 Mixing

How to get sufficient mixing in a series of 12 non-aeration small cells for each MBR bioreactor was one of the challenges in the experiment equipment set-up. One of alternatives considered in the beginning of the set up was to place the miniature submersible pumps to replace mixers. But this option was not taken after further investigation on the amount of pumps to be used, the space to be required and the cost to be involved.

After several attempts and tests, it was finally decided to continue to use the inexpensive 40 rpm, 120 V AC gear motors, which were used in the previous study before. These motors coupled with the tailor-made shafts and impellers achieved a sufficient mixing for non-aeration cells during the operation (Figure 23 and 24).

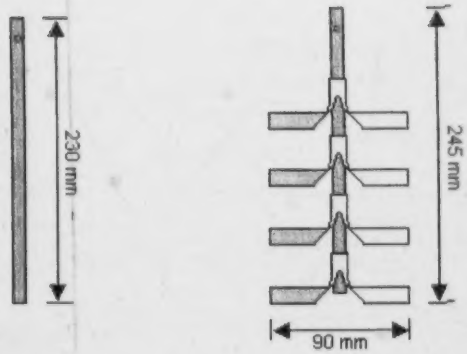

Figure 23. (a) Tailor-made shaft. (b) Tailor-made impeller.

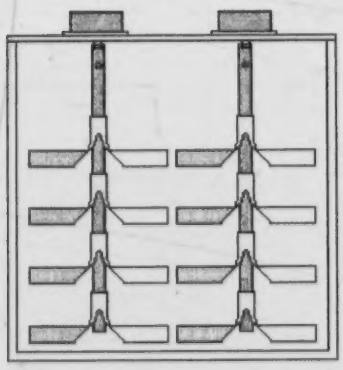

Figure 24. Profile view of mixing in non-aeration cell.

6.4 mm stainless steel tubes were cut to make 230 mm long shafts. 12.7 mm stainless steel tubes were cut into small pieces to construct impellers. The 12.7 mm stainless steel impellers slid over the 6.4 mm stainless steel shafts and were fixed by set screws. In order

to get good mixing by the low rpm motors, two motors were installed for each non-aeration cell, and average 4 impellers were equipped by each motor. Totally 48 motors and 192 impellers were installed for the non-aeration cells of both MBRs. It was proved that the design and installation of the tailor-made mechanical mixers was very successful and sufficient mixing was achieved. Only one motor was out of service and replaced in the whole 92 day continuous operation period.

3.2.5 Safety Control of Liquid Level

A polypropylene float switch was installed in R-cell of each membrane tank to prevent the membrane tank from being drained out when the primary effluent feed was not supplied or the flow path was blocked by accident. The float switches were connected to the computer. Through the computer software Labview 7.0 (See appendix A), the permeate pump would be terminated once the water level decreased to below the float, and would be turned on when the water level came back to above the float. The height of the float switch was set to cover the top header of ZW-10 membrane module in the membrane tank. These float switches were efficient to prevent the membrane tank from draining during the 92 day operation.

3.2.6 Aeration

Sufficient aeration in MBRs was required to provide oxygen for the reduction of BOD and ammonia, and in the mean time to keep adequate mixing of the mixed liquor in each aerobic cells as well as membrane tanks. In the beginning, several trials were made by using neoprene air diffusers for aquariums with either stone or metal net attached to have

enough weight to hold it at the bottom of the aerated cells. The tests were successful, but they were still too complicated for 3.6 L cells. A simple solution for aeration was finally made by the test of a Bubble Wall® aerator found in a special aquarium store. The Bubble Wall® aerators were manufactured by Penn-Plax Inc. They were made of bendable and pliable materials. And the air diffusers have unique characteristics. They can be bent conform to any shape. The surface of the diffusers was very porous and flexible. An uninterrupted flow of bubbles can be produced. The air diffusers can be easily placed at the bottom of water because they were designed with weights to stay in place.

A 900 mm long air diffuser was bent in a shape to cover the full floor (100 mm × 100 mm) of the aerated cell (Figure 25). A 1200 mm long air diffuser were also placed to cover the bottom of the membrane tank (250 mm × 150 mm). One aerator was placed in each aerated cell. There was a total of 26 air diffusers installed in aeration zones of both MBRs. Every four aerators were connected to a mini-manifold with four fine airflow adjustment valves through 6.4 mm vinyl tube. Each set of manifold was connected to the other two manifolds through 9.5 mm polyethylene tube. They were all connected to the air rotameters.

Figure 25. Plan view and profile view of Bubble Wall® aerator.

GBWWTP provided the stable source of the process air supply. The GBWWTP process air supply was continuous flow with about 827 kPa. The air was filtered, dried and used for aeration purpose. It was allowed to use a 2067 kPa air hose to connect the process air line of GBWWTP to the BNR-MBR Bench, where an aluminum alloy manifold was used to equally distribute the process air to both MBRs. Both 6.4 mm and 9.5 mm rigid polyethylene tubes were used to deliver the process air to the mini valve manifold as well as the center air tube in ZW-10 membrane module through four 5.7 m^3/h air rotameters. The rotameter ranged from 0.57 m^3/h to 5.7 m^3/h. The airflow to the 12 aerated cells was controlled and monitored at 1.42 m^3/h to 1.71 m^3/h. The airflow to the center aeration tube in membrane tank was controlled between 1.995 m^3/h and 2.28 m^3/h. Needle valves of upstream of the rotameters were installed to provide fine adjustment to the airflow rotameters. The air diffusers in membrane tank were connected directly to the alloy manifold without passing the air rotameters since the aeration scale up was not the purpose of the study and only four air flowmeters were available at the experiment time. Due to the foaming occurred in the R-cells of the membrane tanks, one 900 mm air

diffuser was installed at the bottom of each R-cell to provide adequate oxygen and mixing after start up. As no mechanical mixers were installed, the sufficient mixing of the mixed liquor in all aeration cells as well as membrane tanks became very important. The aeration systems for both MBRs were efficient during the entire operation period. The average concentration of dissolved oxygen was 3 to 4 mg/L in aerobic zones of bioreactor and 6 to 7 mg/L in membrane tanks, which was well above the nominal requirement of 2.0 mg/L. It was mainly because the adequate mixing required more aeration. No obvious biomass deposits were observed in all aerated cells as well as membrane tanks.

3.2.7 Mixed Liquor Recycle

In both fixed-film and suspend solids growth systems, activated sludge was returned to the system to maintain a proper balance between the food supply and the mass of microorganisms in the system. This balance was the food-to-microorganism ratio (F/M) and was important in the removal efficiency.

In BNR-MBR systems, activated sludge was returned not only for the balance of F/M ratio, but also for nitrate reduction. The mixed liquor recycle was originally drawn from the recycle cell (R-cell) to first cells of pre-anoxic zone (R1), anoxic zone (R2) and aerobic zone (R3) for MBR1 (Figure 26). Recycles for MBR2 was similar to MBR1 except for R1 was from the last cell of the anoxic zone to the first cell of anaerobic zone (Figure 27). R1 of both MBRs was operated at 1Q; R2 was 3 to 4Q; and R3 was 4 to 5Q. Flow rates of recycles were monitored and calibrated weekly by using a graduated cylinder and stopwatch. Mixed liquor was collected from the recycle lines downstream of

the peristaltic pumps for calibrations. Since R-cell was designed to thicken activated sludge and to reduce excess dissolved oxygen, the recycles from R-cell were expected to have a minimum DO concentration and a high MLSS concentration. Furthermore, the safety override float switch installed near the top of R-cell was also expected to avoid the malfunction caused by air bubbles or foam in membrane tank as no aeration was designed in R-cell.

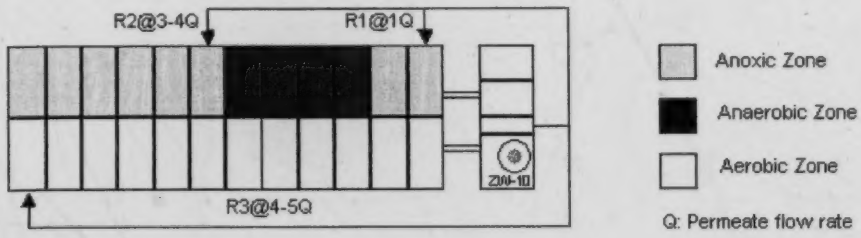

Figure 26. MBR1 recycle configuration before modification.

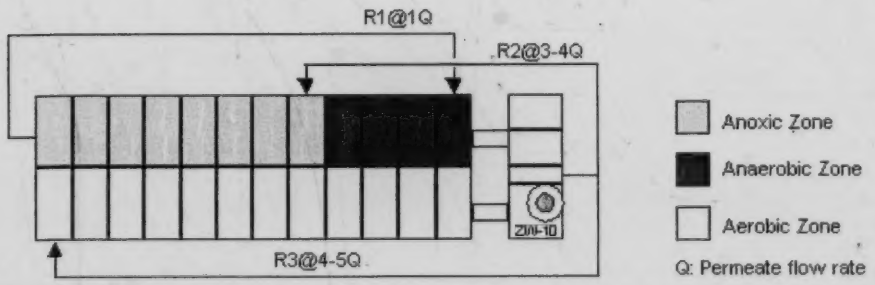

Figure 27. MBR2 recycle configuration before modification.

But in the initial start up period, the foam quickly built up in pre-anoxic zone and anoxic zone for MBR1 and in anoxic zone for MBR2. The first thought concerning these phenomena was that the denitrification of mixed liquor in R-cell caused nitrogen gas bubble rising up when it was recycled to the pre-anoxic zone and anoxic zone. On the top of R-cell, the foam build-up was clearly observed. However, with the further observation, it was found out that the foam was mainly caused by high aeration in membrane tank. As the bottom of R-cell was connected with the bottom of membrane cell, shortcuts occurred when total 7Q to 9 Q of mixed liquor was drawn from the bottom of R-cell. The mixed liquor in R-cell did not circulate well. The depth of mixed liquor in membrane tank was about 650 mm and the consequent water pressure also helped to keep more air dissolved in the mixed liquor at the bottom of the membrane tank. Due to intensive aeration in membrane tank, the recycled mixed liquor from the bottom of R-cell contained excess dissolved air. Similar to the air bubble scum accumulated at the top of R-cell, the air bubbles were released and quickly rose up after it was recycled to the pre-anoxic zone and anoxic zone. The biomass in mixed liquor was also brought up and attached to the surface of air bubbles, and ultimately led to the foam build-up, which resumed very quickly even after cleaning of these non-aeration zones.

As the R-cell did not function properly as expected, the mixed liquor recycles for both MBRs were modified after the initial start up. In MBR1, the mixed liquor recycled to pre-anoxic zone (R1) and anoxic zone (R2) was drawn from the last cell (No.24) of the bioreactor instead of taking from the bottom of membrane tank. Similarly, R2 of MBR2 was also drawn from cell 24 of bioreactor instead. Only internal recycles (R3) of mixed

liquor in aeration zone were still drawn from the bottom of membrane tank. The modification was shown in Figure 28 and 29.

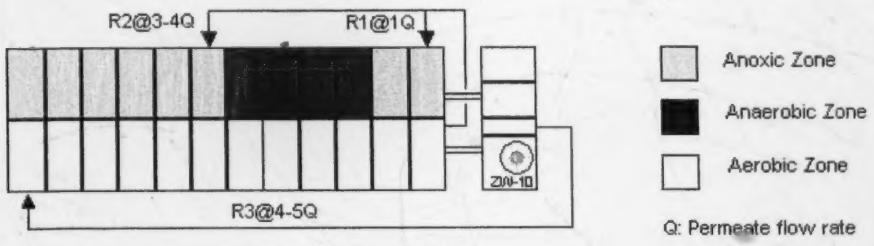

Figure 28. MBR1 recycle configuration after modification.

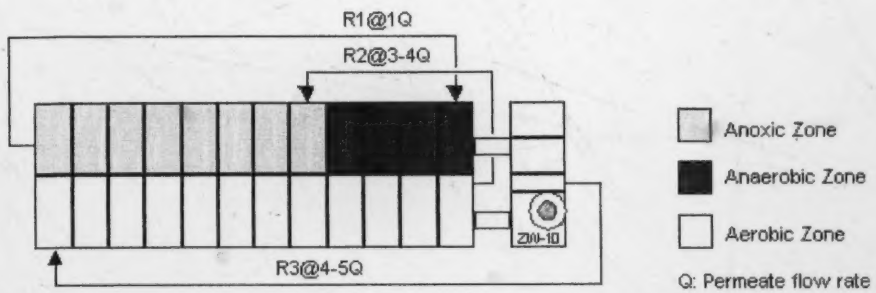

Figure 29. MBR2 recycle configuration after modification.

This modification proved to be very effective. The foam build-up was eliminated right after the recycle was modified. Furthermore, much of the nitrate contained in mixed liquor was intercepted in the last cell of the bioreactor and recycled to anoxic zone before

it went to membrane tank and permeated out through the membrane. This was confirmed by the nitrate profile analysis.

Each recycle was driven by a 600 rpm peristaltic pump capable of a maximum flow rate of 2200 mL/min. Three peristaltic pumps were required for each MBR. Black Neoprene tubing was used for pump head tubing. All recycle inlet and outlet was designed to use plastic push-to-connect fittings. 9.5 mm polyethylene tubes were used for all the recycle lines.

In the later period of the study, in order to further reduce the dissolved oxygen in the returned mixed liquor, two recycle containers were constructed and installed in recycle lines of R1 and R2, respectively, for MBR1. One recycle container was also added to R2 line for MBR2 (Figure 30). The recycle containers were placed on magnetic mixing plates and maintained a complete mixing by using magnetic stirring bars. This design was attempted to give some non-aeration residence time to the recycled mixed liquor before they were returned to pre-anoxic zone and anoxic zone. It was expected that denitrification in both pre-anoxic zone and anoxic zones would be enhanced. The results were not as expected. This was probably due to the limited mixed liquor volume (about 0.5 to 1 L) maintained in the containers by giving only 1 to 2 minutes of residence time.

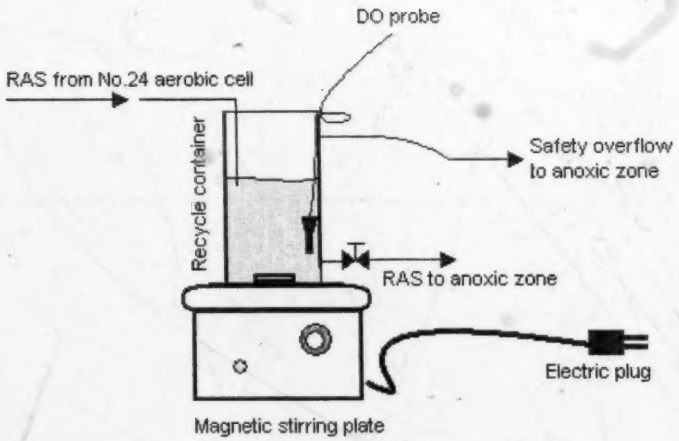

Figure 30. Recycle container.

3.2.8 Foam & Splash Control

The freeboard of the bioreactors was 70 mm tall. Membrane tanks also had lower freeboard, which was 130 mm tall compared to 8500 mm tank height. During water test run, it was found out that water splash reached outside of both bioreactors and membrane tanks due to the aeration bubble explosions. Therefore, with consideration of possible mixed liquor splash and foam, additional freeboard of both bioreactors and membrane tanks was extended by the installation of aluminum sheet around the edge of the bioreactors and membrane tanks. The additional freeboard installed was 200 mm for bioreactor and 300 mm for membrane tanks. The extended freeboard was very effective and protected equipment from any mixed liquor splash during the entire operation period.

No severe foam occurred during the 92 day study. However, some foam were observed in aerobic cells of both MBRs during the late days of the experiment. It was probably due to three unexpected shutdowns. Two were caused by GBWWTP power supply failure and the other one was because the PE line from GBWWTP was out of service and the safety level float was triggered to shutdown the permeate pumps for about 22 hours. The shutdowns caused the sudden changes of the hydraulic loading. Microorganisms became starved for a short period of time and this might have promoted the growth of filamentous bacteria. The change of the hydraulic time from 6 hours to 8 hours may have also contributed to the presence of foam. The foam was firstly controlled by manual cleaning of the aerated cells. The cleaning was not sufficient because the foam resumed quickly after the clean-up of the foam at the top of aerated cells. An effective method to reduce the foam was to increase the rate of wasted sludge (Gold Bar, 2000). With the increase of the wasting sludge (WS) flow rate, more food (PE) entered the bioreactor to compensate the lost liquid and in the meantime the concentration of biomass was reduced. The changing condition was not favorable for the filamentous microorganism. Therefore the foam was ultimately reduced.

The initial light foam occurred at the top of R-cell during the start-up period was controlled by the circulation of the top mixed liquor in R-cell. Two peristaltic pumps were used, each for one MBR. Both inlets and outlet of peristaltic pumps were placed at the top of R-cell. The inlet was inserted into the bottom of the foam layer above the mixed liquor. The outlet was placed above the foam. It was very effective. The air bubbles were quickly broken down after the circulation. Foam in R-cell was reduced.

After the change of recycle lines, two additional 900 mm Bubble-Wall® air diffusers were placed at the bottom of R-cell, the aeration prevented the foaming in the R-cell. No foam occurred in membrane cells during the 92 day operation. It was probably due to the intensive aeration mixing.

3.2.9 Membrane Pump

Two magnetic drive, 24 Volts direct current (DC) gear pumps left from the previous study were used in the experiment. One was for MBR1 and the other was for MBR2. The pump production rate could be controlled by an adjustment knob at the back of the pump. The pump was capable of producing flow rates as high as 2600 mL/min. The flow rates of the pump ranged from 240 mL/min to 480 mL/min during the operation. The backflush flowrate was set to keep the same production rate. Due to the backflush involved in the operation, water rotameters were not applicable. Other flow meters were not available at the time of the experiment. Therefore the pump flow rate was calibrated manually by using a stop watch and a graduated cylinder periodically. A series of flow rates were matched to a series of speed scale numbers in an extended range of speed adjustment dial knob for each MBR installed in the automation control box.

The pumps were connected to the analog to digital (AD) circuit board in the computer through an automation control box, which consisted of a 24 V DC power supply equipment and solid-state relays, electrical resistances and other electronics. A Labview 7.0 was used as the computer control software (Refer to Appendix A). The pumps were automatically controlled to run a user inputted permeate production interval and

backflush interval. The interval ratio of production/backflush used in this experiment was 450 s to 15 s or 225 s to 7.5 s. The ratio of 112.5 s to 7.5s was also occasionally used in late days of operation for a HRT of 4 hours.

Each pump was set for two safety triggers. One was the preset minimum water level trigger and the other was the maximum suction pressure trigger. The water level trigger was to prevent the membrane tank from running dry. The trigger was controlled by a safety override float switch located in the middle of the top header of ZW-10 module in R-cell. When the mixed liquor level was below the float switch in R-cell, the float switch triggered and the permeate pump was disabled until the mixed liquor level recovered. The maximum suction pressure trigger was set for 48 kPa to prevent the suction pressure out of the operation pressure range and caused the damage to membrane fibres.

3.2.10 Wasting Sludge Control

The excess sludge was wasted continuously by using one 100 rpm peristaltic pump for each MBR (Figure 31). The flow rate of wasting sludge was set for 4 mL/min, which was equivalent to a theoretical solid residence time (SRT) of 20 days. The calculation was under the assumption that the concentrations of MLSS were identical in all different zones of bioreactors and membrane tanks. Under this assumption, the wasting sludge flow rate was obtained by dividing the total volume of mixed liquor by 20 days. The actual SRT was corrected after experiment by multiplying 0.78, which was the ratio of the average MLSS concentration in MBR to MLSS concentration in membrane tanks.

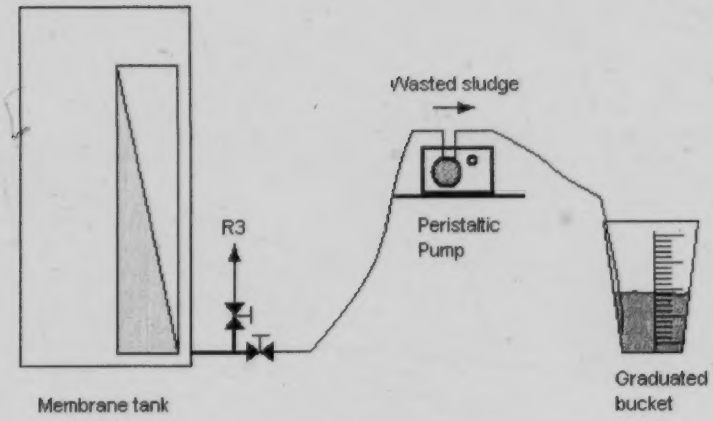

Figure 31. Sketch for wasting sludge configuration.

The flow rates were calibrated periodically by using a stopwatch and a 10 mL graduated cylinder to measure the volume of sludge collected in the cylinder in one minute. The wasting sludge was collected in a 20 L calibrated bucket for each MBR and was emptied daily or once every two days. The wasting sludge in the bucket included the sludge from the continuous wasting pump and from any manual sludge cleanings. It ensured the accuracy of the total amount of the sludge wasted and the actual SRT calculated.

3.2.11 **Autosamplers**

GBWWTP loaned one autosampler and one small fridge to the project. The automated composite sampler was configured to collect a BNR-MBR feed sample according to the sample schedule. The sampler was connected to the manifold after the filter. A 10 L sample bottle was placed in the autosampler. A 250 mL sample was taken every 15

minutes. The total amount of samples varied between 4 L and 8 L, depending on different hydraulic residence times. The composite sample collected in autosampler was delivered to the GBWWTP laboratory for analyses.

Two solenoid valves were designed and configured to collect the composite permeate samples (Figure 32). On one side solenoid valves were connected to the backpulse container through 9.5 mm polyethylene tube, and on the other side were connected to the permeate bottles in sample fridge by 6.4 mm vinyl tubes. Two 8 L sample bottles were placed in the sample fridge. The 6.4 mm vinyl tubes went to the sample bottles through the holes cut on the top of the fridge. Following the permeate sampling schedules, the time intervals for open and close of solenoid valves were programmed into the control software in the computer. The solenoid valves were calibrated on the site prior to the startup. About 250 mL permeate sample was collected every 15 minutes according to the sampling schedule inputted in the computer control software. The permeate from the backflush container went through the solenoid valve to the sample bottle when the solenoid was open. When the solenoid valves closed, the permeate residues left in the tubes after the solenoid valves were released by gravity to the sample bottles. The vent tube after solenoid valves provided the atmospheric balance to let the residue flow.

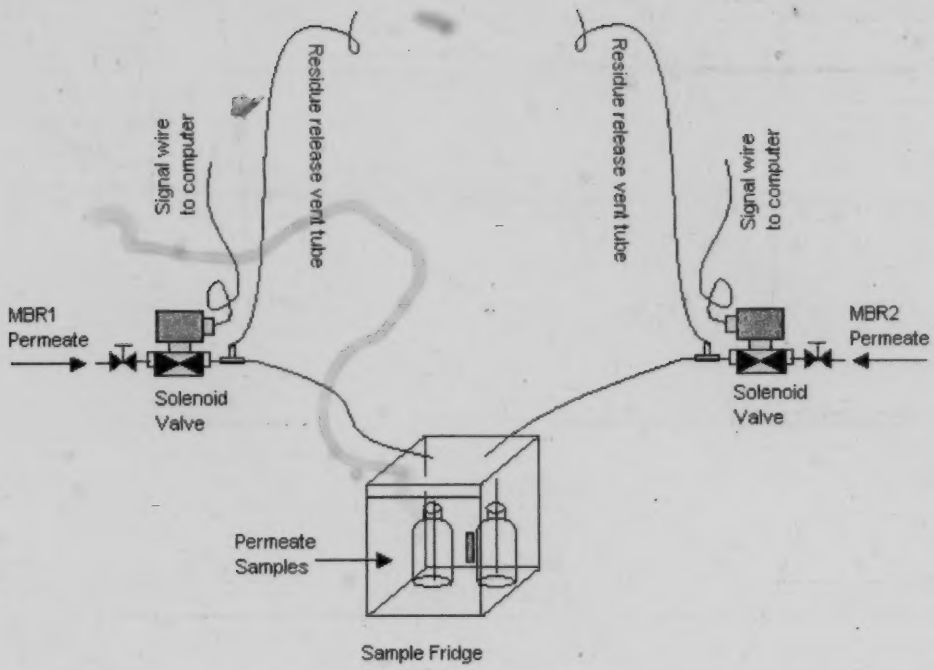

Figure 32. Sketch for automated collection of composite permeate samples.

3.2.12 Online Monitoring

3.2.12.1 Dissolved Oxygen Monitoring

Four analog YSI 54A dissolved oxygen (DO) meters were used to monitor the DO in aeration zones and membrane tanks of both MBRs. Each MBR used two meters. One was placed to the aeration zone of bioreactor and the other was placed to the membrane tank. All the meters were connected to the control box, where they were further connected to the AD circuit board of the computer. For each meter, a correction factor was determined by comparing the reading of the computer display to the analog reading on the meter. Then the factors were inputted into the control software in the correction factor fields

under the DO readings. The DO readings in computer display were consistent with the DO readings in the meter after the correction factors were determined and inputted.

The first difficulties occurred in DO monitoring were that the DO readings were out of range and fluctuated wildly. It seemed that the probe was contaminated with dirt. After several attempts to replace the membrane and refill the potassium chloride solution, the problems were still not resolved in the beginning of the study. Finally it was found out that the potassium chloride solution was not of good quality. It was crystallized after the meter probes were refilled for a few days. The four meters worked well when the potassium chloride solution was changed. During the study, it was also observed that the probes used for the YSI DO meters were not reliable for DO online monitoring in high MLSS concentration conditions. The sludge easily deposited on the probes. The probe membrane fouling occurred quite often, and ultimately led to inaccurate DO readings. The counter-approach was that the DO readings were monitored manually and recorded periodically only when no membrane fouling was present either by new membrane replacement and calibration or by shaking and cleaning.

The meters were calibrated using BOD dilution water from the GBWWTP laboratory, where the DO of the BOD dilution water was determined for calibration of the lab meters. Four capped 256-mL BOD bottles were used to take the BOD dilution water to the MBR site for meter calibrations. The meters were calibrated when the membrane was replaced or when the accurate readings needed to be recorded. Since the aeration in both bioreactors and membrane tanks were also exercised as mixing to keep the mixed liquor

suspension, the DO in aeration zones of both MBRs were excessive for the biological activities. The average DO ranged from 3 to 4 mg O_2/L in aeration zones of bioreactors and 6 to 7 mg O_2/L in membrane tanks.

3.2.12.2 Temperature Monitoring

A tailor-made temperature senser probe was installed in the feed manifold to monitor the PE feed temperature. The probe was connected to the AD circuit board of the computer through the computer control panel in the control box. The temperature readings were displayed and recorded in the computer. The probe was calibrated using ice-chip mixed water heated by a heating plate. The probe was tied with a mercury temperature thermometer and they were inserted into the same position in the slowly heated water held in a 3 L glass container. When the temperature was slowly increasing, the data readings in volts from the computer and the temperature readings in degree Celsius from the thermometer were recorded. A linear relationship was obtained through the excel regression to convert the voltage reading (V) into temperature reading (°C). The calibration result was illustrated in Figure 33.

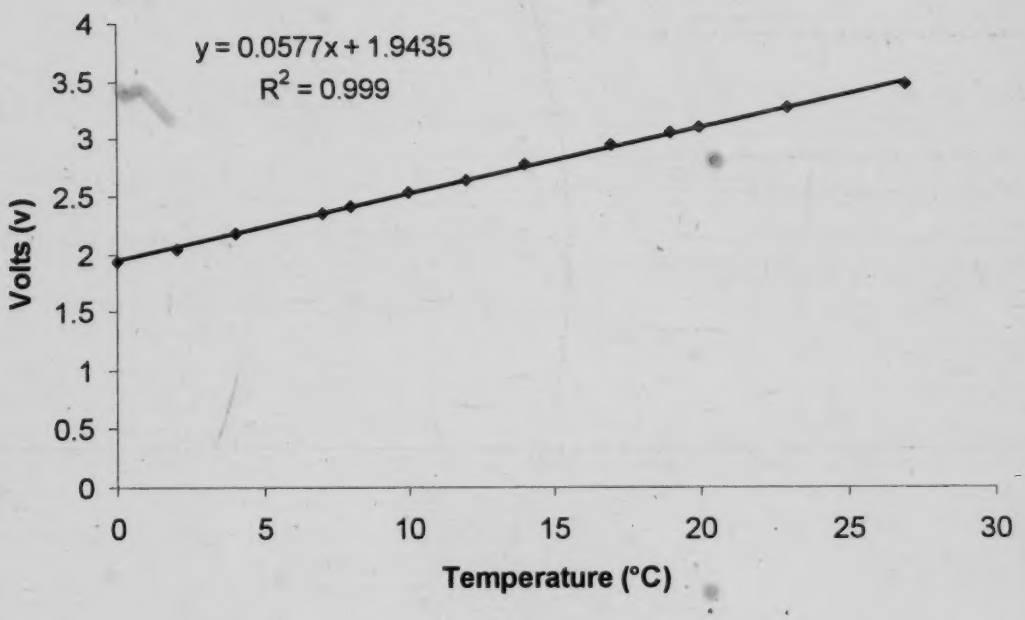

Figure 33. The linear relationship of the calibration curve for the temperature probe.

The probe was made of a 50,000 ohm thermo-resistor. The thermo-resistor was put through a 100 mm 9.5 mm copper tube, where the thermo-resistor protruded in a small paper mold tightly attached to the end of the copper tube. The prepared epoxy sealant was poured into the copper tube. When the epoxy sealant was cooled down, both the thermo-resistor and its wire were embedded in a hard epoxy coat, which protected the thermo-resistor and its wire from moisture damage. In the meantime, a thin epoxy coat of the thermo-resistor provided the good heat conductivity to ensure the accuracy of the probe (Figure 34).

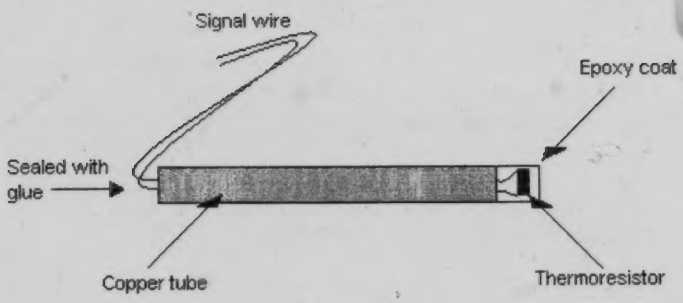

Figure 34. The illustration of the temperature probe.

3.2.12.3 Pressure Monitoring

Two Cole-Parmer pressure transducers from the previous experiment were used to monitor both the negative pressure and the positive pressure for permeate production and backpulse. The transducers were directly connected to the top header of ZW-10 membrane module through a 70 mm stainless steel tube (6.4 mm). The pressure readings were displayed instantly in forms of numbers and graphs in the computer. The readings were also recorded in every 5 or 10 seconds depending on the backpulse intervals. An excel data file was generated daily by the control software in the computer at time 0:00 (midnight). The production / backpulse intervals were inputted into the control software and could be modified at any time.

The pressure transducers were calibrated using a pressure calibrator rented from Accutech Rental Ltd. The transducers were capable of measuring pressures of – 101 kPa to 207 kPa. In this experiment, the maximum pressure for ZW-10 module was (±) 62 kPa.

The pressure calibration range was – 62 kPa to 68.9 kPa. In the calibration, the transducer voltage readings in the computer were recorded against the actual pressure reading in the pressure calibrator. A linear regression was obtained in an excel file for each pressure transducer. The linear equations were then inputted into the computer control software to convert the voltage readings of the transducers to pressure readings. The calibration curves for pressure transducers were illustrated in Figure 35 and 36.

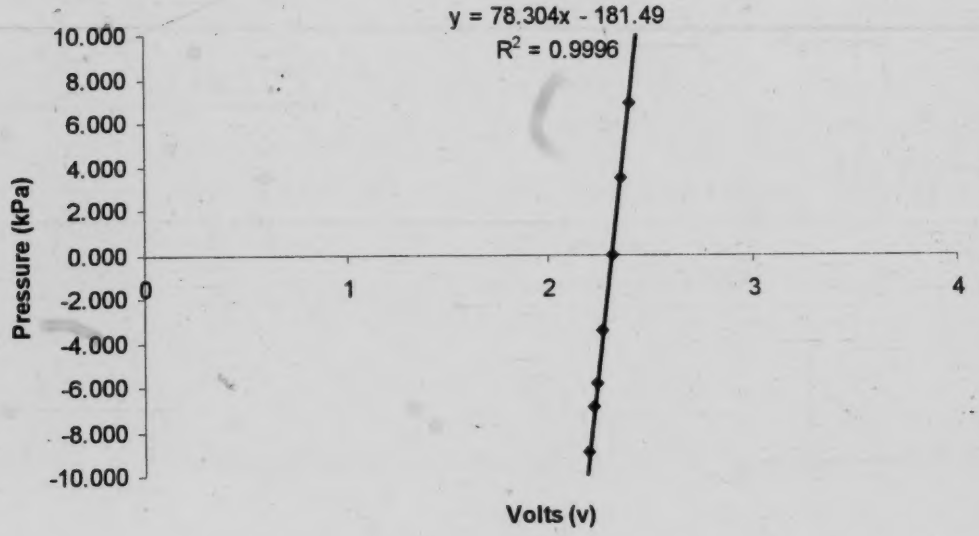

Figure 35. Pressure calibration curve for transducer #1.

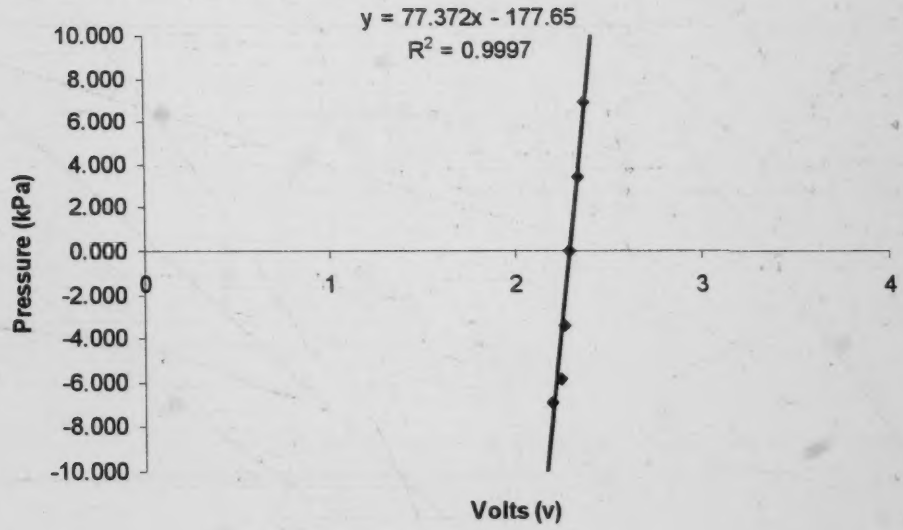

Figure 36. Pressure calibration curve for transducer #2.

3.3 Unit Test Runs

3.3.1 Membrane Integrity Test

Zenon Environmental Inc. supplied ZW-10 membrane modules for the previous study. Three ZW-10 membrane modules were left and stored in a big container in the membrane group lab. The membrane modules were individually identified by serial numbers labeled on the bottom headers. The modules were submerged in DI water all the time and Sodium hypochlorite was added as anti-bacteria agent periodically. As the ZW-10 modules used for the previous experiment were not in a very good integrity quality and the remaining modules were stored for almost three years, the integrity test was required to check if the modules were still suitable for the experiment.

Two methods were used to do the membrane integrity tests. The first one was the air bubble test. The modules submerged in the DI water were pressurized to 62 kPa and were visually checked if there were any bubbles occurred. No bubbles were present during the test. The second method was the pressure decay test. Figure 37 illustrated the integrity test system for ZW-10 modules. Two Cole-Parmer pressure gauges were used in the system for parallel reading and confirmation. All the valves and fittings were push-to-connect products and they were easily connected and disconnected. The modules were placed outside of the water during the test.

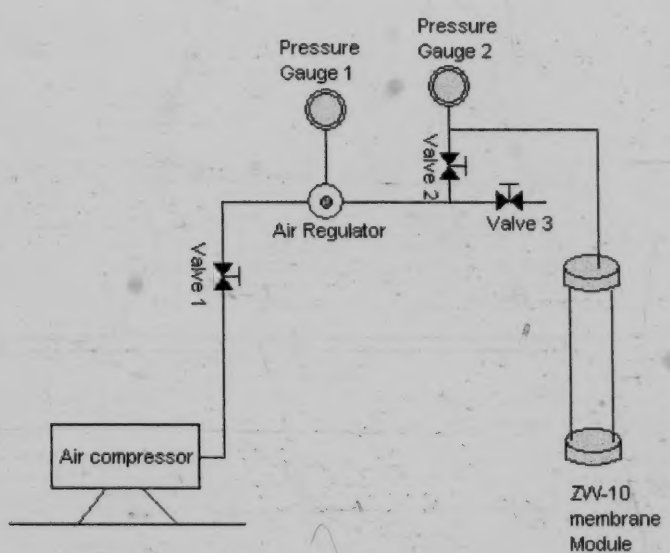

Figure 37. Sketch of the membrane integrity test system.

The test procedure was described as the following steps:

(1) Open valve 1 and air regulator and close valve 2 and valve 3.

(2) Start the air compressor to increase the air pressure to 20 psi.

(3) Close valve 1 and air regulator and open valve 3 to release the air.

(4) Close valve 3 after the air is released and open valve 2.

(5) Open valve 1.

(6) Slowly open the air regulator to increase the air pressure by the rest pressurized air in the system. The air pressure gauges are carefully watched and the air pressure is increased to 14 kPa, 28 kPa, 41 kPa and ultimately 62 kPa.

(7) Close valve 1 and start to record the pressure drop for 10 minutes.

The average pressure decay rates were 0.34 kPa/min for W102046 and 0.83 kPa/min for W102047. No comparable standard reference available for the integrity test of ZW-10 module from the supplier. However, the test results seemed acceptable based on the current understanding of the literature review. No apparent openings or cuts were observed in both membrane modules. W102046 was used for MBR1 and W102047 was used for MBR2. The pressure decay curves are shown in Figure 38 and 39.

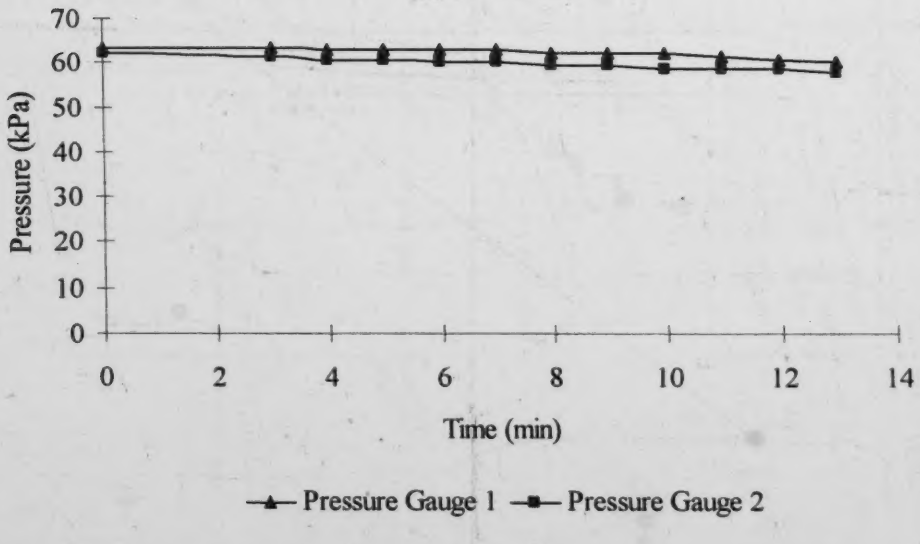

Figure 38. Pressure decay curve for ZW-10 membrane module W102046 for MBR1.

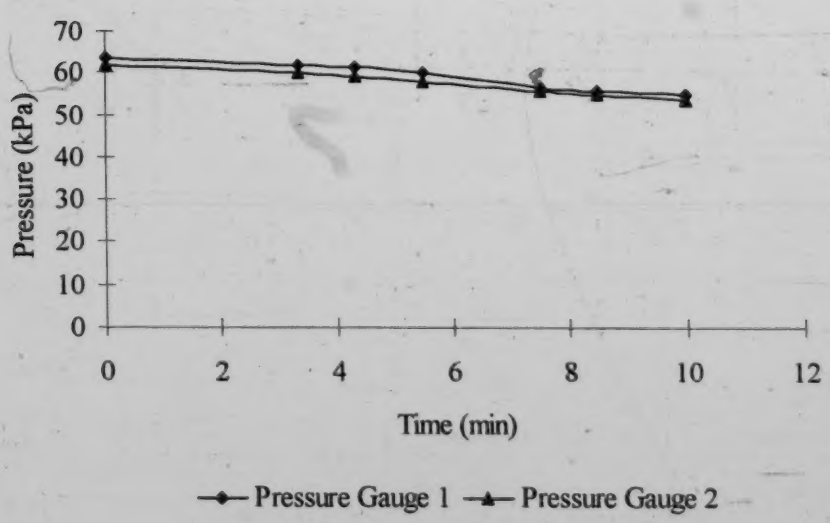

Figure 39. Pressure decay curve for ZW-10 membrane module W102047 for MBR2.

3.3.2 Tracer Tests

In order to find out the flow pattern and the actual HRTs of the newly constructed BNR-MBR systems, seven tracer tests were completed prior to the startup of the experiment (Table 8).

Table 8. The setup conditions of the tracer tests for both MBRs.

Theoretical HRT (hours)	Operating time (hours)	Operating conditions	Production /Backpulse	Tracer agent added (Na^+)
6	8	Q=330 mL/min, No recycles	No backpulse	3600 mg/L 100 mL
4	6	Q=480 mL/min, R1=0.5Q, R2=1.5Q, R3=2.5Q	15 min / 10s	7200 mg/L 100 mL
6	8	Q=330 mL/min, R1=1Q, R2=3Q, R3=5Q	15min / 30s	14400 mg/L 200 mL
8	10	Q = 240 mL/min, R1=1Q, R2=3Q, R3=5Q	30min / 20s	14400 mg/L 200 mL

Sodium chloride was used as a tracer agent. Certain amount of high concentration (Na^+) sodium chloride was added into the first cell of the bioreactor when the tracer test started at time 0. The first tracer test was done only for MBR1 without recycles and backpulse. The HRT was 6 hours. Two conductivity meters was used for the online monitoring of the Na^+ concentration. One was placed in the last cell of bioreactor. The other was placed in a 250 mL beaker, which collected permeate from the membrane module. The 250 mL beaker was placed in the 2.5 L container, which allowed the permeate overflow to be discharged from the beaker. A time series of samples were collected from the 6.4 mm

valve upstream of the beaker. The sampling intervals were 1 to 10 minutes depending on the Na^+ concentration appeared. The ion-flame photometer was used to determine the Na^+ concentration of each sample. A mercury thermometer was also inserted into the beaker to monitor the permeate temperature. Some photos of tracer test experiment are listed in Appendix B.

T_{10} is the hydraulic residence time when 10% of tracer was out of the system. T_{10} is an important reactor design parameter. Ideal plug flow bioreactors have significantly higher T_{10} values and would theoretically allow for more complete denitrification. The actual hydraulic residence time was the time when 50% of the sodium ion added in the first cell was out of the system. It was called T_{50}. In the first tracer test (HRT=6 hours, no backpulse and recirculations), T_{10} was 4.06 hours. T_{50} for bioreactor was about 5.20 hours and T_{50} for the whole BNR-MBR system including the bioreactor and membrane tank was 6.23 hour, which was quite close to the theoretical HRT 6 hours. The higher T_{10} value and T_{50} (close to theoretical HRT) indicated that the BNR-MBR system had a good plug flow pattern for a HRT of 6 hours without recycles and backpulse. Figure 40 illustrates the tracer curves with conductivity probes placed in the last cell of bioreactor and permeate container without recirculations and backpulse at theoretical HRT of 6 hours.

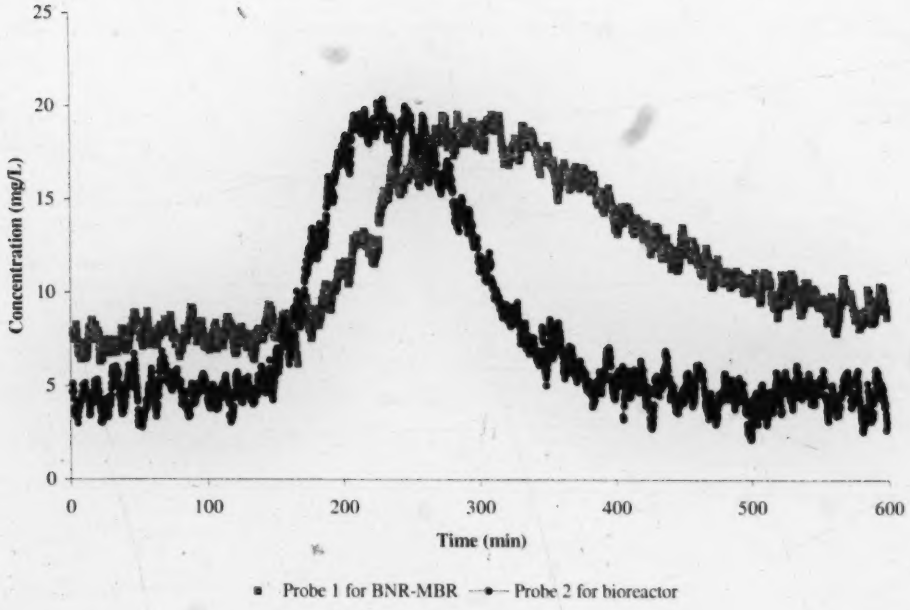

Figure 40. Tracer test curves for both the bioreactor and the BNR-MBR by online conductivity meters without recirculations and backpulse at theoretical HRT of 6 hours.

The first test proved the successful plug flow design of the BRN-MBR system. However, the true plug flow for a reactor is very difficult to achieve in practice due to the axial dispersion, especially the mixing and recycles involved. The other three tracer tests for both MBRs were required to emulate the planned operating conditions to find out the actual HRTs. It was observed that with backpulse and recirculations, T_{10}, T_{50} and T_{75} all decreased. The T_{10} for HRT of 6 hours decreased 54% from 4.06 hours to 1.85 hours. This can be explained that recirculations led to the flow pattern of BNR-MBR reactor shifted from like a plug flow pattern to like a complete mixing flow pattern. The more

recycles were involved, the less plug flow pattern occurred in the BNR-MBR systems. Table 9 lists the tracer test results for three different HRTs of both MBRs.

Table 9. Seven tracer test results.

HRT	Unit	MBR1			MBR2			Remarks
		T_{10}	T_{50}	T_{75}	T_{10}	T_{50}	T_{75}	
6	hours	4.06	6.23	8.86	N/A	N/A	N/A	No backpulse & recirculations
4	hours	1.31	3.80	6.70	1.26	3.47	5.66	With backpulse & recirculations
6	hours	1.85	4.71	7.26	1.42	4.80	8.16	
8	hours	2.12	6.54	>10 .26	1.92	6.05	10.04	

Tracer test curves are illustrated in Figures 41 to 46 for both MBRs at HRTs of 4, 6, 8 hours.

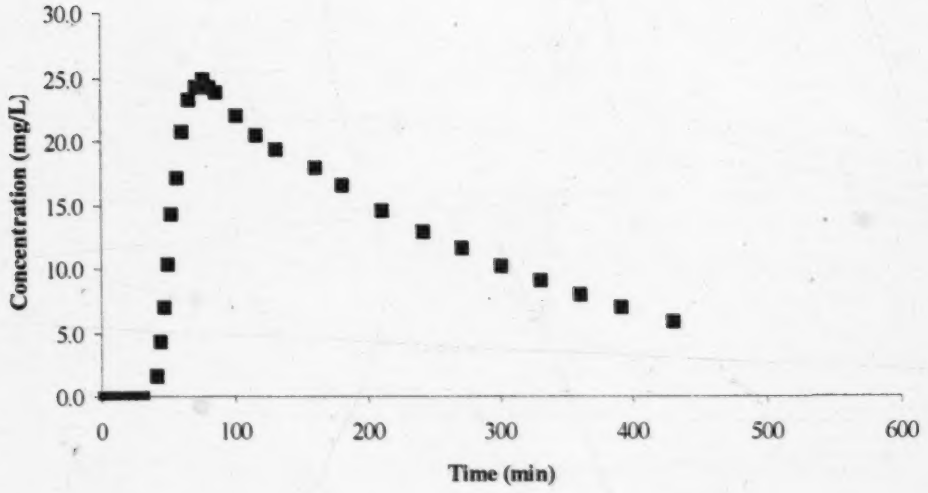

Figure 41. Tracer test curve for MBR1 at HRT of 4 hours with recirculations and backpulse.

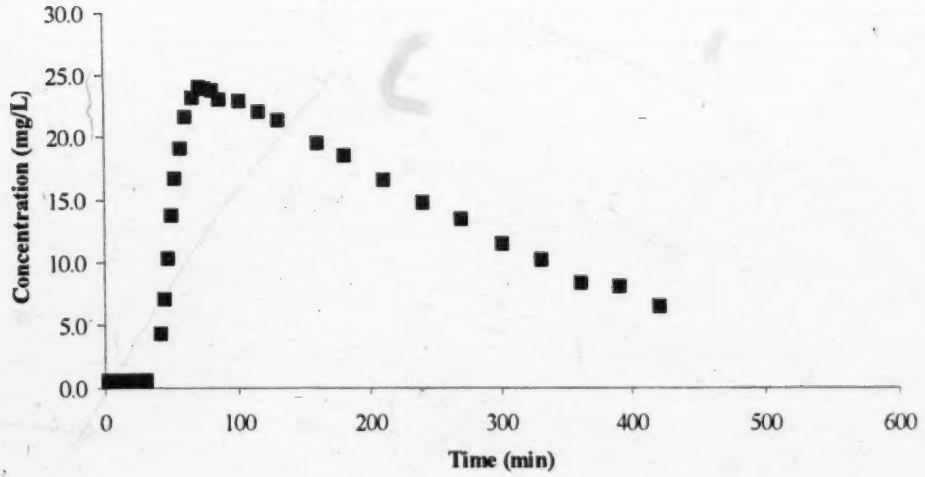

Figure 42. Tracer test curve for MBR2 at HRT of 4 hours with recirculations and backpulse.

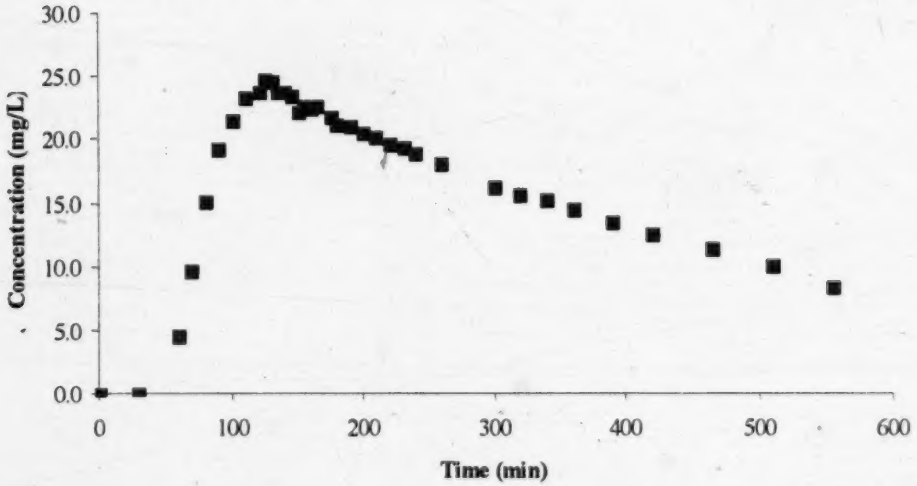

Figure 43. Tracer test curve for MBR1 at HRT of 6 hours with recirculations and backpulse.

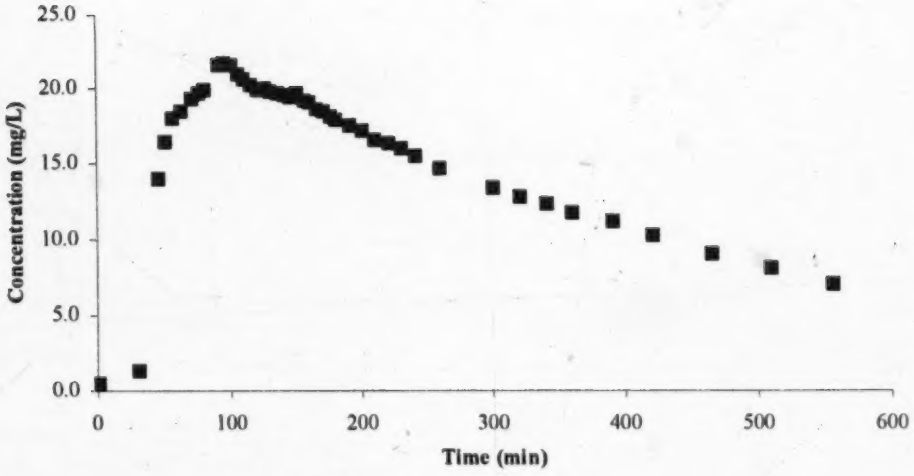

Figure 44. Tracer test curve for MBR2 at HRT of 6 hours with recirculations and backpulse.

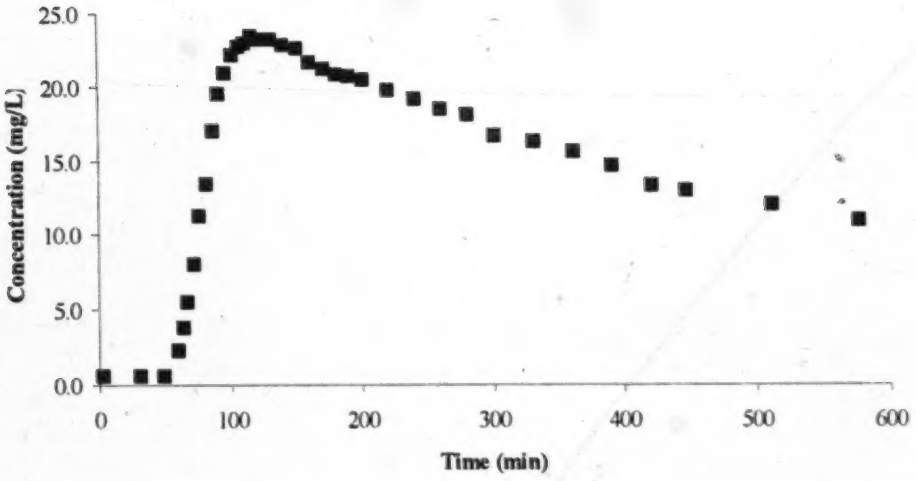

Figure 45. Tracer test curve for MBR1 at HRT of 8 hours with recirculations and backpulse.

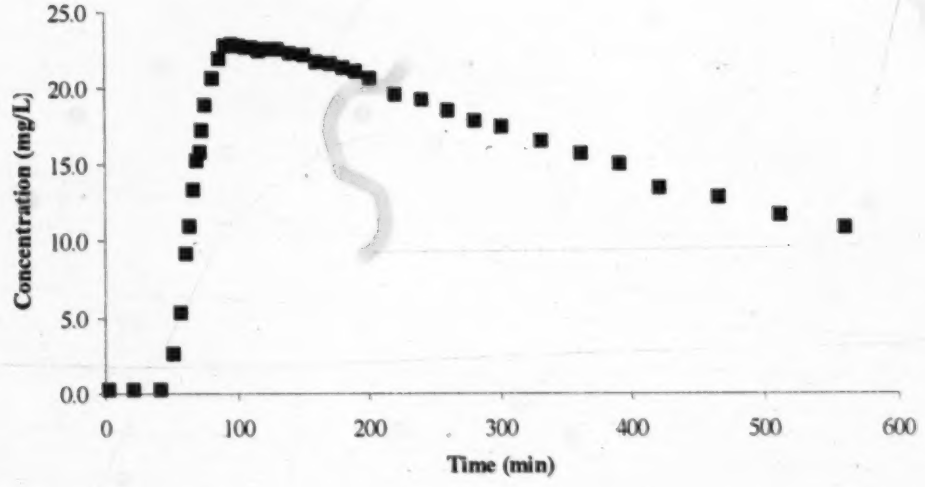

Figure 46. Tracer test curve for MBR2 at HRT of 8 hours with recirculations and backpulse.

3.4 Sampling Design

Sampling protocol and sampling schedule were worked out prior to the start of the experiment. The analytical methods were based on methods outlined in *Standard Methods for the Examination of Water and Wastewater, 19th Edition* (APHA *et al.*, 1995). Sample data validation and acceptance were subject to the quality control guidelines and limits of the GBWWTP laboratory. The procedures permit tracing a sample through all steps from collection to analysis and display of results (*Standard Methods*, 1995).

The objective of sampling analyses was to obtain data to document the performance of the MBR unit with focus on nutrient removal. Data collected must be representative, reproducible, defensible and useful. The sample control and documentation procedures are to ensure that the objectives of sampling analyses are fulfilled.

3.4.1 Sample Analyses Plan

GBWWTP laboratory provided the routine analyses (three times a week), which included TSS, VSS, BOD_5, COD, soluble COD, TKN, NH_3-N, TOXN, TP, VFA, total coliform, fecal coliform for MBR-feed analyses; MLSS, MLVSS for mixed liquor; and TSS, BOD_5, COD, VFA, TKN, NH_3-N, TOXN, TP, total coliform, fecal corliform for MBR-permeate. The research student carried out the the routine analyses of pH for both feed and permeate, turbidity and particle count for the permeates and the profile analyses for mixed liquor. The mixed liquor profile analyses (once a week) included MLSS, MLVSS, soluble COD, nitrate nitrogen, ammonia nitrogen, ortho-phosphate in different zones of

both MBRs. The analytical items, applied methods, schedules and responsible parties are described in Table 10.

Table 10. Sample plan for BNR-MBR experiment.

Analyte	Abbr.	MBR feed	MBR permeate	Mixed Liquor					Responsible	
				Pre-Anoxic zone	Anaerobic zone	Anoxic zone	Aerobic zone	Memb tank	Research Student	Gbar Lab
Routine analyses										
Total suspended solid	TSS	x/1	x/1							x
Volatile suspended solid	VSS	x/1								x
Mixed Liquor SS	MLSS						x/7* x/2**	x/2*	x*	x**
Mixed Liquor Volatile SS	MLVSS						x/2**			x**
Five-day CBOD	CBOD5	x/1	x/1							x
Total Chemical oxygen demand	COD	x/2	x/2							x
Soluble COD	COD-s	x/2								x
Total Kjeldahl nitrogen	TKN	x/2	x/2							x
Ammonia nitrogen	NH3-N	x/2	x/2							x
Total oxidized nitrogen	TOXN	x/2	x/2							x
Total phosphorus	TP	x/2	x/2							x
Volatile fatty acid	VFA	x/1								x
Turbidity	NTU		x/5						x	
PH	PH	x/1	x/1						x	
Total coliform	CO-T-M	x/1	x/1							x
Fecal coliform	CO-F-M	x/1	x/1							x
Profile analyses:										
Ammonia nitrogen	NH3-N	x/1		x/1	x/1	x/1	x/1	x/1	x	
Nitrate nitrogen	NO3-N	x/1		x/1	x/1	x/1	x/1	x/1	x	
Ortho-phosphate	O-PO4-P	x/1		x/1	x/1	x/1	x/1	x/1	x	
soluble COD	COD-s	x/1		x/1	x/1	x/1	x/1	x/1	x	
MLSS	MLSS			x/1**	x/1**	x/1**	x/1**	x/1**		x
MLVSS	MLVSS			x/1**	x/1**	x/1**	x/1**	x/1**		x

Note: x/n=samples per week

3.4.2 Sample Collection

Data collection activities should indicate events that occur during sample handling that may affect the integrity of the samples (U.S. EPA, 1998). The samples should be small enough in volume to be transported conveniently and handled in the laboratory while still accurately representing the material being sampled (*Standard Methods*, 1995). Table 11 indicates some recommended sample collection conditions for wastewater (U.S. EPA, 2001)

Table 11. Recommended volumes, container types, preservation and holding times by U.S. EPA.

Analysis	Amt.	Container Type	Preservative	Max. Holding Time
BOD_5	2 L	Polyethylene	ice	2 days
COD	1 L	Polyethylene	H_2SO_4 (pH<2), ice	28 days
Nitrate	2 L	Polyethylene	ice	2 days
Nitrite	1 L	Polyethylene	ice	2 days
Nutrients (Ammonia, TKN, NO2, NO3, -N, total phosphorus)	2 L	Polyethylene	H_2SO_4 (pH<2), ice	28 days
pH	500 mL	Polyethylene	NA	<15 mins
Phosphate - ortho	1 L	Polyethylene	ice	2 days
Solids - Settleable	2 L	Polyethylene	ice	2 days
Turbidity	500 mL	Polyethylene	ice	2 days
Oxygen - dissolved	40 mL	G	NA	<15 mins

Composite samples are taken to reflect the average conditions in a large volume of sample whose chemical properties may vary significantly over the course of a day. Grab samples are taken all at once, at a specific time and place at peak flow conditions (Hauser,

1996). In the study, all routine samples were composite samples and the rest were grab samples. Six L composite feed sample was collected in a 10 L polyethylene container located in the center of an autosampler each time. The ice pack was placed in the autosampler beside the sample bottle before the sample collection started. Six L composite permeate samples were collected from backpulse containers in 8 L polyethylene bottles in a refrigerator. 200 mL coliform sample were collected from the upstream of backpulse containers randomly before the samples were delivered to GBWWTP.

Mixed liquor samples (100 mL each) were also collected randomly from different zones of MBRs using 60 mL syringes before the sample delivery to the laboratory. Permeates for pH, turbidity randomly in 200 mL polyethylene bottles. Permeate for particle count was collected in 500 mL glass bottles. The collection schedule was tried to match the GBWWTP schedule. The routine samples were normally collected every afternoon to midnight of Sunday, Tuesday and Thursday and delivered to GBWWTP laboratory in the mornings of Monday, Wednesday and Friday. The collection schedule of composite permeate samples was designed to fit that of the composite feed samples. From the tracer test, T_{50} was the best practical time interval for sample collection between the feed and permeates. Table 12 describes the detailed routine sample collection schedule programmed into both autosampler and computer control software. All sample bottles including sterile sample bottles were provided by GBWWTP laboratory.

Table 12. The collection schedules of routine samples.

HRT (hours)	T_{80} (hours)	MBR-feed Sampling Time	Day	Permeate Sampling Time	Day
4	3.5	14:00 – 18:00	Sundays Tuesdays Thursdays	17:30 – 21:30	Mondays Wednesdays Fridays
6	5	12:00 – 18:00	Sundays Tuesdays Thursdays	17:00 – 23:00	Mondays Wednesdays Fridays
8	6.5	10:00 – 18:00	Sundays Tuesdays Thursdays	16:30 –23:55	Mondays Wednesdays Fridays

3.4.3 Sample Locations

The test requirements of the research project determined the sample location. Samples should be taken wherever the mixing is best, and the sample was of uniform quality. There were 24 cells in each bioreactor. The numbering of the cells started from feed (cell 1) to the end of aeration zone (cell 24). The sampling locations for both MBRs are indicated in Table 13.

Table 13. Locations of sample collection in BNR-MBR experiment.

Samples	Location @ MBR1	Location @ MBR2	Collection
MBR-feed	MBR feed line	MBR feed line	Composite, auto
MLSS/MLVSS, Pre-anoxic zone	Cell 2	N/A	Grab, manual
MLSS/MLVSS, Anaerobic zone	Cell 4	Cell 4	Grab, manual
MLSS/MLVSS, Anoxic zone	Cell 11	Cell 11	Grab, manual
MLSS/MLVSS, Aerobic zone	Cell 14 & Cell23	Cell 14 & Cell 23	Grab, manual
MLSS/MLVSS, Membrane tank	Membrane tank	Membrane tank	Grab, manual
Permeate	Backpulse container	Backpulse container	Composite, auto

3.4.4 Field Blanks and Field Duplicate

Field blank is a blank used to provide information about contaminants that may be introduced during sample collection, storage, and transport. A clean sample, carried to the sampling site, exposed to sampling conditions, returned to the laboratory, and treated as an environmental sample. Field duplicate is an additional sample taken near the routine field sample to determine total within-batch measurement variability (U.S. EPA, 1998).

In the study, field blanks and field duplicates were not used based on the following reasons:

- The collection and transportation of samples were strictly controlled.
- The analytical values of samples were relative high, compared to potential background values.
- Field blanks and field duplicate were supposed to be used once or two times only for permeate BOD samples, but the analytical BOD results of permeate samples during the study were very low and almost all of the samples were less than 2 mg O_2/L, which indicated the integrity of the sample collections and distributions.
- Analytical cost saving.

3.4.5 Documentation

Table 14 indicates the description of sample names by MBRs, locations and delivery dates.

Table 14. Sample name description.

Samples	MBR 1 (GBWWTP process)	MBR 2 (UCT process)
PE feed	F_date (mm/dd/yy)	
Permeate	1P_date (mm/dd/yy)	2P_date (mm/dd/yy)
Pre-anoxic zone	1PR_date (mm/dd/yy)	
Anaerobic zone	1AE_date (mm/dd/yy)	2AE_date (mm/dd/yy)
Anoxic zone	1AN_date (mm/dd/yy)	2AN_date (mm/dd/yy)
Aerobic zone	1AO_date (mm/dd/yy)	2AO_date (mm/dd/yy)
Membrane tank	1MT_date (mm/dd/yy)	2MT_date (mm/dd/yy)

Information on the collection and handling of samples were documented in sample log sheet (Table 15) and sent to GBWWTP laboratory together with sample deliveries.

Table 15. Sample log sheet.

Sample Log Sheet for BNR-MBR Project

Sample Log Sheet No. _____ Date _____

Sampler: (*signature*) _____ **ANALYSES REQUIRED**

				Routine Analyses																Profile Analyses					
Sample Name	**Time when sample was taken**	**Total Volume (mL)**	**Preservative**	**TSS**	**VSS**	**MLSS**	**MLVSS**	**BOD_5**	**COD**	**Soluble COD**	**TKN**	**NH_3-N**	**TOXN**	**TP**	**VFA**	**Turbidity**	**pH**	**Total Coliform**	**Fecal Coliform**	**Ammonia Nitrogen**	**Nitrate Nitrogen**	**Ortho-phosphate**	**Soluble COD**	**MLSS**	**MLVSS**

Remarks

Received by: _____

Date & time:

The operation events were documented in the field log. Appendix C summarized the major operation events, which may potentially influence the performance of the BNR-MBR systems. Sample labels were clearly marked following the name guideline of Table 14. Reports of analytical results from GBWWTP laboratory were issued officially twice a month (Appendix D)

3.5 Analytical Methods

Table 16 and 17 outlines all the analytical methods applied for both routine analyses and profile analyses. Analytical methods were based on *Standard Methods for the Examination of Water and Wastewater, 19th Edition* (APHA *et al.*, 1995) and the Alberta Environment Centre's (AEC) Methods Manual for Chemical Analysis of Water and Wastes (Dieken *et al.*, 1996). Standard operating procedure (SOP) and the quality control guidelines and limits of GBWWTP laboratory was strictly followed for the analytical testing of all samples.

3.5.1 TSS Determination

The TSS method of GBWWTP laboratory was based on *Standard Methods* 2540D. A 25 mm fiberglass filter and a crucible were used in the test. The sample was filtered through a weighted 25 mm fiberglass filter and a crucible, the residue retained on the filter was dried to a constant weight at 103 to 105 °C. The gain of the weight was the total suspended solids. As TSS in permeate was expected to be very low, a measured large volume of sample was required to pass through the filter. The detection limit was 0.6 mg/L.

Table 16. Analytical methods for routine samples.

Sample	Abbr.	Analytical methods
Total and Volatile Suspended Solid	TSS, VSS	St.Methods 2540D and 2540E
Mixed Liquor Suspended Solid	MLSS	St.Methods 2540D (Paper filtration)
Mixed Liquor Volatile SS	MLVSS	St.Methods 2540E (Paper filtration)
Five-day Carbonaceous Biochemical Oxygen Demand	$CBOD_5$	St.Methods 5210B
Total Chemical oxygen demand	COD	St.Methods 5220D/HACH 8000
Soluble COD	COD-s	St.Methods 5220D/HACH 8000
Total Kjeldahl nitrogen	TKN	AEC Methods 235
Ammonia nitrogen	NH3-N	AEC Methods 219
Total oxidized nitrogen	TOXN	AEC Methods 2359
Total phosphorus	TP	St.Methods 4500-P F
Volatile fatty acid	VFA	U.S. EPA Methods 5035
Turbidity	NTU	St.Methods 2130 B
PH	PH	St.Methods 4500-H+ B
Total coliform	CO-T-M	Membrane Filter-St.Methods 9222 B
Fecal coliform	CO-F-M	Membrane Filter-St.Methods 9222 D

Table 17. Analytical methods for profile analyses

Analyte	Abbr.	Analytical methods
Ammonia nitrogen	NH_3-N	Nessler HACH method 8038
Nitrate nitrogen	NO_3^--N	St.Methods 4500-NO^{3-} C St.Methods 4500-NO^{3-} D
Ortho-phosphate	O- PO_4^{3-}-P	St. Methods 4500 / HACH 8048
Soluble COD	COD-s	St.Methods 5220D/HACH 8000
MLSS	MLSS	St.Methods 2540D (Paper filtration)
MLVSS	MLVSS	St.Methods 2540E (Paper filtration)

3.5.2 VSS Determination

The VSS method was based on *Standard Methods* 2540E. The residue from TSS method was ignited to constant weight at 550 °C. The weight lost on ignition was the volatile solids. VSS gave an indication of the amount of organic matter present in the solid fraction of wastewater.

3.5.3 MLSS/MLVSS Determination

MLSS/MLVSS methods were similar to TSS/VSS methods. GWWTP laboratory used 95 mm ashless filter paper to replace 25 mm small fiberglass filter as the high solid concentration in the mixed liquor, which was called "paper method". A quick test was also carried out during the operation using the centrifuge/rapid method for monitoring for determining the MLSS concentration. The results of this method was not used for reporting.

3.5.4 BOD_5 Determination

The BOD_5 determination was based on *Standard Methods* 5210B. A 256 mL diluted sample was incubated at 20 ± 1 °C for 120±2 hours in a temperature controlled stainless steel water bath. Dissolved oxygen was measured before and after incubation. BOD_5 was the difference between initial and final DO. The detection limit was 2 mg/L at GBWWTP laboratory.

3.5.5 COD Determination

COD determination was carried out by GBWWTP laboratory using *Standard Methods* 5220 D for both MBR-feed and permeate samples. The same method was applied to the profile analyses for the mixed liquor in different zones. The 0.45 μm filter was used for the MBR-feed soluble COD and the mixed liquor. The detection limit of COD was 2 mg/L for low reference (COD ≤150 mg/L) and 5 mg/L for high reference range (>150 mg/L) at GBWWTP laboratory.

3.5.6 Ammonia Determination

The automated phenate colorimetric method (AEC Method 219) was used by the GBWWTP laboratory for the routine analyses of permeate. The detection limit was 0.013 mg/L. Nessler HACH method 8038 adapted from *Standard Methods* 4500-NH3 B & C was used by the research student to perform the profile analyses for the mixed liquor. The mixed liquor was centrifuged first and then the supernatant was filtered through a 0.45 μm membrane filter. The filtrate was used for profile analyses. The detection limit was 0.017 mg/L NH_3-N.

3.5.7 Total Oxidized Nitrogen Determination

The GBWWTP laboratory used the automated cadmium reduction, diazotization colorimetric method (AEC method 2359) for the routine analyses of NO_3^- and NO_2^- in permeate. The detection limit of TOXN was 0.006 mg/L. For profile analyses of NO_3^- in mixed liquor in different zones, Ion Chromatographic Method (*Standard Methods* 4500-NO_3^- C) and Nitrate Electrode Method (4500- NO_3^- D) were used.

3.5.8 Total Kjeldahl Nitrogen Determination

The total Kjeldahl nitrogen in both feed and permeate samples was determined by GBWWTP using AEC method 235. The detection limit of TKN was 0.032 mg/L at GBWWTP laboratory.

3.5.9 Total Phosphorus Determination

GBWWTP laboratory utilized *Standard Methods* 4500-P F to determine the total phosphorus in the MBR feed and permeate samples. The detection limit of TP was 0.016 mg/L at GBWWTP laboratory.

3.5.10 Coliforms

The determination of both total coliforms and fecal coliforms was carried out by GBWWTP laboratory for MBR-feed and permeate samples. *Standard Methods* 9222 B and 9222 D were used for total coliforms and fecal coliforms, respectively. The detection limit of both coliforms was 1 CFU/100 mL at GBWWTP laboratory.

3.5.11 Turbidity

The research student utilized *Standard Methods* 2130 B to determine turbidity of permeate samples using a HACH 2100AN turbidimeter at GBWWTP laboratory. The turbidity of Deionized Water was always measured for comparison.

3.5.12 Particle Count

Particle Counter provided by the membrane lab of the Environmental Engineering and Science Program was used to determine the particle count of both permeates. Deionized water was also tested for particle count each time to have a comparison reference with permeates.

3.5.12 pH

The research student utilized an Acumet 950 pH meter to determine the pH of MBR-feed, permeate samples based on *Standard Methods* 4500 H+B. The pH meter was calibrated using pH buffers 4, 7 and 10.

3.5.13 Volatile Fatty Acid Determination

The determination of volatile fatty acids (acetic, propionic and butyric) was done by GBWWTP laboratory for MBR-feed samples using a gas chromatograph coupled with a flame ionization detector (GC-FID), Direct Injection Method. The detection limit was 10 mg/L for acetic acid, 11 mg/L for propionic acid, 10 mg/L for butyric acid at GBWWTP laboratory.

3.5.14 Reactor Profile Analyses

In order to further understand the reactions occurred in different zones, mixed liquor samples were taken from each zone and membrane tank once a week. As described in Table 17, the analyses included soluble COD, ammonia nitrogen, nitrate nitrogen, ortho-phosphate and MLSS/MLVSS. To have a better understanding of microbiology of the

biomass in mixed liquor, a full-scale activated sludge analysis was carried out by GBWWTP laboratory for the mixed liquor samples taken from aeration zone and membrane tanks of both MBRs at the last day of the experiment (April 29, 2004).

3.6 Operation Plan

3.6.1 Plan of Operation Conditions

The planned operation conditions for MBR1 and MBR2 are summarized in Table 18.

Table 18. The planned operation conditions.

Operation condition	MBR 1 (GBWWTP Process)	MBR 2 (UCT Process)	Remarks
Sludge Age (days)	15 to 20	15 to 20	By continuous sludge wasting @4 mL/min (118 L/20 days)
Theoretical HRT (hours)	6, 8, 10	6, 8, 10	4 hours @ day 1 to 15, 6 hour after day 15
Recirculation 1 (% inflow)	100 (aerobic zone to preanoxic zone)	100 (anoxic zone to anaerobic zone)	50 @ day 1 to 15, 100 after day 15
Recirculation 2 (% inflow)	200 (aerobic zone to anoxic zone)	200 (aerobic zone to znoxic zone)	100 @day 1 to 15, 200 after day 15
Recirculation 3 (% inflow)	400 (membrane tank to head of aerobic zone)	400 (membrane tank to head of aerobic zone)	200 @ day 1 to 15, 400 after day 15
DO concentration (mg/L)	2 to 5	2 to 5	5 @ day 1 to 15, 2 after day 15 depending on foaming observation
Production (min)	15	15	May vary on site cond.
Back flush (seconds)	30	30	May vary site cond.

3.6.2 The Start-up Strategy for Activated Sludge Condition

The activated sludge for the start-up was planned to be withdrawn from the relevant zones of GBWWTP bioreactor. The strategy for the sludge training in the first 15 days was to use short hydraulic residence time (4 hours) to provide more food (high F/M ratio) for the microbe growth, higher DO concentration (5 to 10 mg/L) to prevent the growth of filaments, lower recirculation to increase the plug flow pattern.

3.6.3 Flow Rate

In BNR-MBR systems, the flows entering the systems were dependent on the flows of permeate leaving the system. Permeate flow rate was governed by the design flux of ZW-10 membrane module when the membrane area (0.93 m^2) was fixed. According to tracer test runs, the total effective volume of each MBR was about 116 L to 118 L. In this experiment, a series of HRTs was selected from 4 hours to 10 hours. The original plan of permeate flow rates and operation flux rates is indicated in Table 19. However, during the experiment, HRT of 10 hours was not tested and a HRT of 4 hours was performed in the last stage of the experiment.

3.6.5 Dissolved Oxygen

During the operation, the dissolved oxygen was planned to keep at 2 mg/L to 5 mg/L and higher at the headend of aeration zone and lower at the backend of aeration zone. However, in the startup period, the DO level was planned to maintain at a relative higher level to prevent potential foaming.

Table 19. The original plan for permeate flow rate and operation flux.

Sludge Age (20 days)	Planned HRT (hours)	Influent/Permeate Flow (mL/min)	Operation Flux (L/m^2h)
0.75 (Day 1 to 15)	4	460	30
0.25 (Day 16 to 20)	6	322	21
Sludge Age 2 (Day 20 to 40)	6	322	21
Sludge Age 3 (Day 40 to 60)	8	241	16
Sludge Age 4 (Day 60 to 80)	10	193	12

3.6.6 The Strategy for Potential Foaming Control

An "overfeed" strategy was planned to use for the potential foaming control especially in the startup period. The concept of "overfeed" was to provide sufficient food and oxygen to microbes to prevent the growth of filament microorganisms. The F/M ratio shall be raised by raising PE inflow rate, i.e. decreasing HRTs. The dissolved oxygen can be maintained up to about 10 mg/L (16 ° C, 1 atm) depending on the operation condition.

4 Results and Discussion

The BNR-MBR pilot plants were successfully operated from January 27 to April 29, 2004. Three HRTs of 6 hours, 8 hours and 4 hours were tested. Appendix C outlines all the major operation events during the study. High performances of both MBR pilot plants were observed. The primary goals for the project were achieved. The results of the study indicates that the BNR-MBR technology is a realistic, practical treatment option for municipal wastewater at GBWWTP plant.

4.1 Start-up, Commissioning and Production Control

4.1.1 Water Test Run

The water test run was fully operated in planned production conditions. The only difference from the real production was using utility water instead of primary effluent as feed and no sludge was involved. The first water test run was carried out on January 6, 2004. The membrane tank of MBR1 was broken during the test run. The reason was that the thickness of the membrane wall was made under the design specification 6.4 mm. The manufacturer agreed to replace two membrane tanks at no cost. The planned startup date was therefore delayed for about half a month. After the new membrane tanks were installed, a second water test runs for both MBR1 and MBR2 were successfully completed during January 24 to 26. During the water test run, all the equipment including pumps, motors, aerators, instruments were continuously running for 72 hours. All the flow rates of pumps were calibrated with their dial numbers. The autosamplers for the feed and permeates were also calibrated and tested. Few problems were found during the

water test run. After the 3-day water test run, an orange color appeared on the surface of membrane fibres of both modules, which indicated a considerable amount of ferric oxide presented in utility water. The second water test runs worked well in all functions as expected. Some Photos for water test runs can be seen in the attachment B.

4.1.2 MBR Feed Preparation

The primary effluent from the PE channel of #1 bioreactor was supplied to the MBR site through a newly constructed 25 mm pipe. The pipe was connected to the MBR feed system by a flexible plastic tube. A short piece of tube connected to the inside outlet of a feed tank was straight up in order not let the filled mixed liquor back-flow to the feed tank. Both feed tanks were filled up with PE until the overflow level. The PE feed kept entering the feed tank and the overflow was finally discharged through the overflow tank.

4.1.3 Sludge Preparation

In order to get a good sludge for the start-up and to possibly shorten the sludge acclimation period, it was decided to take the sludge from the relevant zones of the GBWWTP bioreactor #10, which had the best performance at that time. GBWWTP was running a winter mode BNR operation, which turned the anoxic zone into aerobic zone to enhance the nitrification. Therefore the MBR sludge for non-aeration zones was only taken from the non-aeration zone area between the pre-anoxic and anaerobic zone of GBWWTP #10 bioreactor. The MBR sludge for aerobic zone was taken from the 4^{th} path of #10 bioreactor. Three 20 L buckets, 12.7 mm ethylene tubes and a peristaltic pump were used to withdraw the sludge from the top of #10 bioreactor. Many difficulties were

overcome during the sludge preparation. As the outside temperature was about – 30 ° C on January 27, 2004 and the #10 bioreactor was the most distant tank to the MBR site, the time for sludge preparation was longer than expected. 16 buckets of sludge were transported from the #10 bioreactor to both MBRs bucket by bucket through a 500 m long tunnel. The peristaltic pump placed at the top of the #1 bioreactor had to keep running in order to prevent the freezing of the pump tubing. Both MBR bioreactors and membrane tanks were filled at the end of the day and were prepared for a full operation.

4.1.4 Permeate Production

The permeate productions of MBR1 and MBR2 were started at 14:45 and 17:00, respectively on January 27, 2004. The permeate production of both MBRs was continuous for 92 days. They were stopped at 10:00 on April 29, 2004. The MBR operations were divided into three stages according to the theoretical retention times of 4, 6 and 8 hours. Table 20 summarizes the operating conditions for both MBRs. Some photos of the BNR-MBR pilot plants were taken during the production and are presented in Appendix B.

4.1.5 Aeration and DO control

The air supplies for the aerobic zones and membrane center aeration tube were measured by air rotameters. The airflow for the aerobic zone of each bioreactor was controlled from 1.42 m^3/h to 1.71 m^3/h. The airflow for the membrane center aeration tube was between 2.0 m^3/h to 2.14 m^3/h. However, the air supplies for the 1.2 m air diffusers at the bottom

of membrane tanks were not measured due to the lack of the rotameters. The aeration was controlled by visual observation to provide sufficient mixing to keep suspension in

Table 20. The actual operating conditions for MBR1 and MBR2.

Operating parameters	Units	Stage I HRT=6 hours		Stage II HRT=8 hours		Stage III HRT=4 hours	
		MBR1	MBR2	MBR1	MBR2	MBR1	MBR2
Stage period	Day	14 to 45	14 to 45	46 to 57	46 to 57	58 to 92	58 to 92
Permeate flow rate (Q)	mL/min	325	325	244	244	460	460
flux	L/m^2h	21	21	16	16	30	30
Suction Pressure	psi	-1.38 to -1.63	-0.33 to -1.61	-0.95 to -1.09	-0.18 to -0.71	-2.19 to -3.54	-2.06 to -3.86
Backpulse Pressure	psi	1.16 to 1.30	0.8 to 2.47	1.40 to 1.46	2.38 to 2.11	2.42 to 3.8	2.8 to 3.76
Recirculations	Q	R1=1Q R2=2.2Q to 3Q R3=3.7Q to 5Q	R1=1Q R2=2.1Q to 5Q R3=3.7Q to 5Q	R1=1Q R2=3Q to 4Q R3=5Q	R1=1Q R2=3Q to 4Q R3=5Q	R1=1Q R2=3Q to 4Q R3=4.3Q to 5Q	R1=1Q R2=3Q to 4Q R3=3.5 to 4.8Q
SRT	Days	14	14	15	15	14	14
MLSS	mg/L	4030 to 9260	4290 to 8260	4700to 7980	4880 to 7940	4240 to 9980	3480 to 9680
MLVSS	mg/L	3510 to 6990	3270 to 6130	3460 to 6000	3550 to 5680	2680 to 7270	2030 to 7092
DO	mg O_2/L	3 to 7	3 to 7	3 to 7	3 to 7	3 to 7	3 to 7
Average Organic Loading	Kg BOD/kg MLVSS day	0.224	0.211	0.337	0.234	0.255	0.358
Wasting Sludge Flow	mL/min	4	4	4	4	4	4

membrane tanks. The dissolved oxygen was about 3 to 4 mg/L in aerobic zone and about 7 mg/L in membrane tank. The DO online monitoring was not very effective since the probes was quickly fouled in the mixed liquor. Therefore, the DO meters were checked frequently and the probes were shaken in the mixed liquor prior to the DO measurement. It was a challenge to keep a low DO in cell #24, where the returned nitrate mixed liquor was withdrawn. The sufficient mixing had to be maintained in aerobic zones and membrane tanks by aeration, the DO was difficult to reduce. Additional recycle

containers were installed to provide the returned nitrate mixed liquor non-aeration residence time to allow the reduction of DO. The results were not as expected since the effective volumes of recycle containers were limited (500 mL to 1000 mL).

4.1.6 Solid Retention Time Control

SRT was one of main operating parameters in the study. The initial goal was to have a SRT of 15 to 20 days. As the TSS in permeate was always lower than detection limit, the loss of solid from permeate was neglected. Three sources of biomass removal were accounted for in the SRT calculations, which included: (a) continuous wasting sludge (WS) flow; (b) mixed liquor sample removal; (c) some sludge cleaning. The biomass removal from the WS flow and sludge cleaning were all collected in graduated 20 L buckets. The buckets were emptied once a day or once every two days. The amount of sludge emptied was recorded each time. The volumes of mixed liquor samples were also recorded when the mixed liquor samples were withdrawn from MBRs. Although the SRT was largely depended on the WS flow rate, considerations of sample removal and sludge cleaning provided more accurate SRT calculations.

The WS flow rate was set up in a way to reach a SRT of 20 days under the assumption that the MLSS concentrations in different zones and membrane tanks were consistent. However, the actual SRT was obtained based on the SRT equation 1 ($SRT = V * X_{ave} / Q_w * X_w$). From the MLSS profile analyses and the volume distributions of different zones, the ratio of average MLSS concentrations X_{ave} to the MLSS concentrations X_w in membrane tanks was calculated out. The ratios of X_{ave} / X_w for MBR 1 and MBR 2 were

0.79 and 0.78, respectively. Two ways of SRT calculations were used. One was based on daily amount of wasted sludge and the other was based on the accumulated amount of wasted sludge. The average SRTs of both calculations are listed in Table 21.

Table 21. Average SRTs for both daily and accumulation WS basis.

Stages	SRT on daily WS basis (days)		SRT on accumulated WS basis (days)	
	MBR1	MBR2	MBR1	MBR2
I: HRT=6h	16	17	14	14
II: HRT=8h	19	19	15	15
III: HRT=4h	14	16	14	14

Both SRT results are illustrated in Figure 47 and 48. The SRT calculated on daily WS basis was more fluctuated than the SRT calculated on accumulated WS basis. The former may reflect more of the changes of process conditions on the wasting sludge rates. The latter may be closer to true SRTs over a certain period of time.

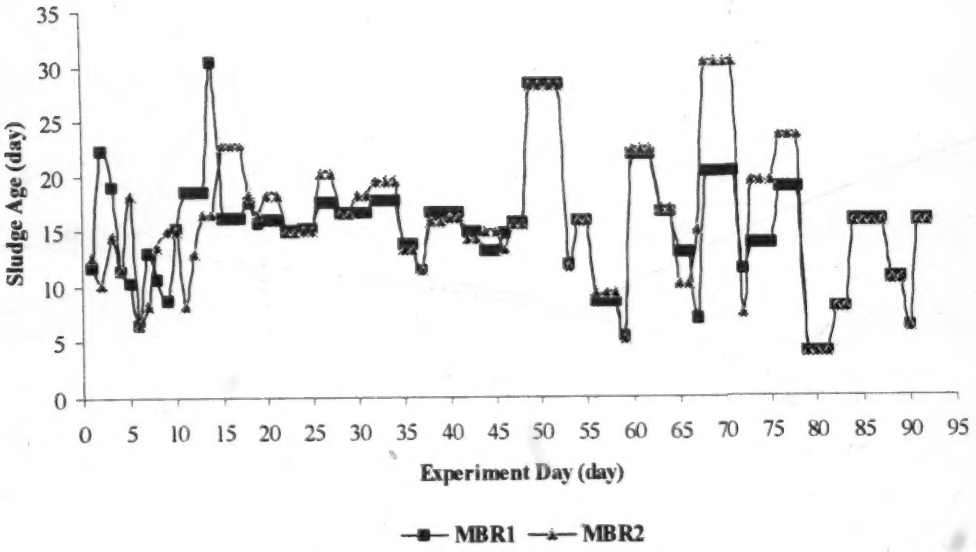

Figure 47. The SRT curves on daily WS basis.

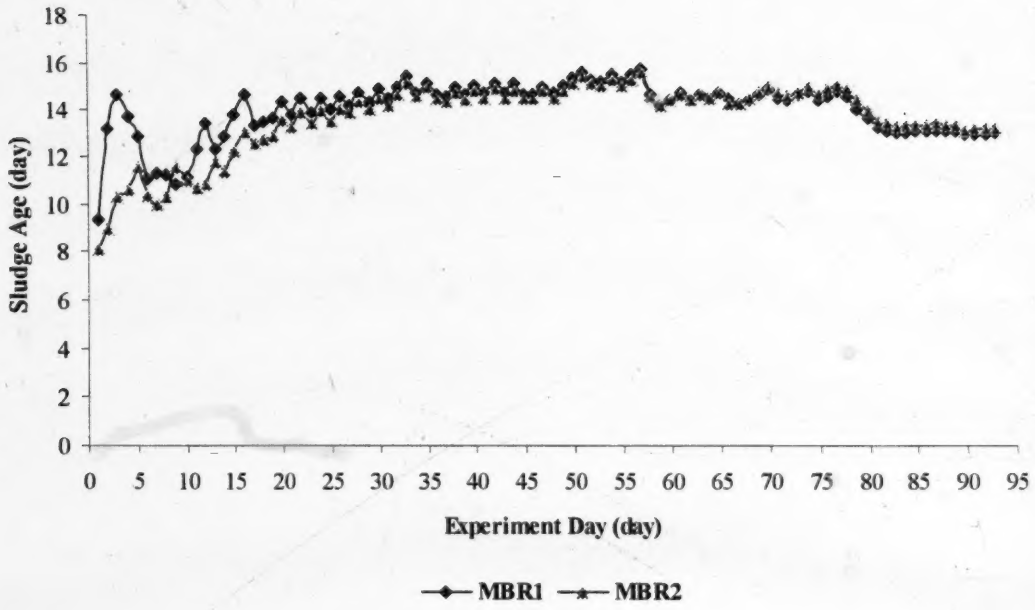

Figure 48. The SRT curves on accumulated WS basis.

4.1.7 Mixed Liquor Solids Concentration Monitoring

The mixed liquor solids are suspended floc mass, which are comprised of biomass, biodegradable volatile suspended solid, cell debris, nonbiodegradable volatile suspended solid, and inert inorganic total suspended solids. In the study, the concentration of mixed liquor solids was not the controlled process parameter. However, in order to better understand the changes of process conditions, the daily monitoring of mixed liquor suspended solids was carried out using a centrifuge method. GBWWTP provided the research student the access to its daily operating centrifuge facilities. A linear relationship was developed by relating the volume percentages of settled sludge under centrifuge condition of 2600 rpm and 15 minutes to the MLSS concentrations obtained from the

GBWWTP laboratory. The MLSS result from the centrifuge test was only for the operation monitoring purpose as it was obtained quickly after the mixed liquor sample was taken. Figure 49 and 50 present the linear regression curves of mixed liquor solids concentrations versus the centrifuge volume ratio in aerobic zones of both MBRs.

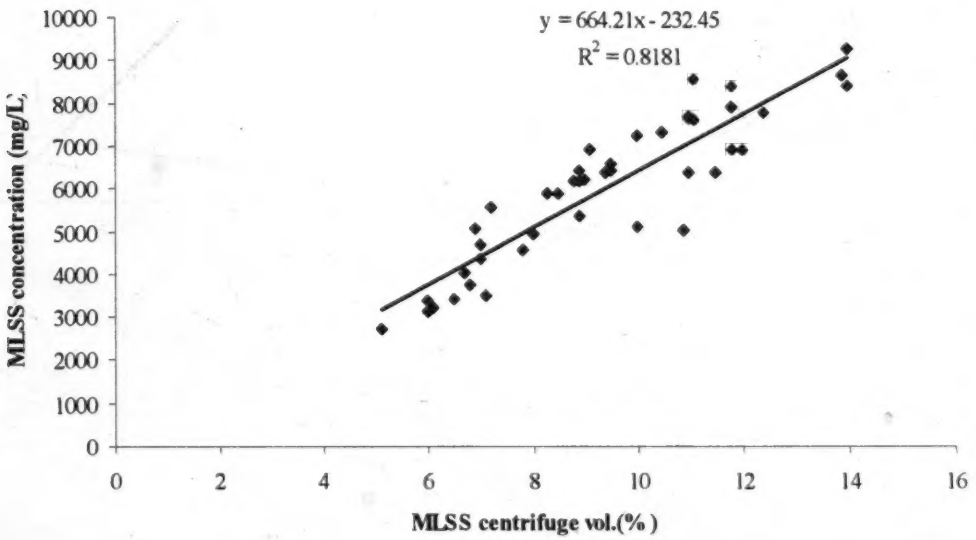

Figure 49. MLSS centrifuge curve for MBR1.

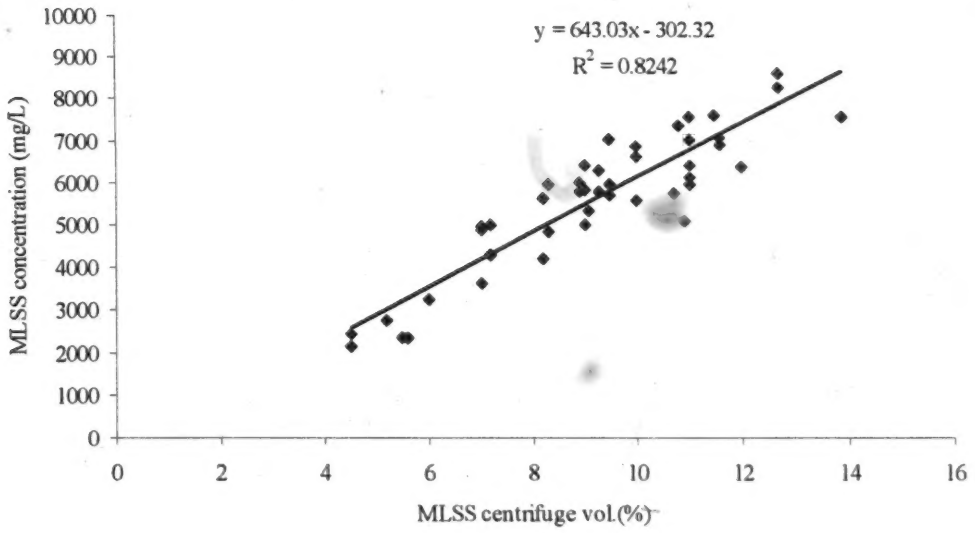

Figure 50. MLSS centrifuge curve for MBR2.

The tests of reported mixed liquor solids concentration were carried out by GBWWTP laboratory. The biomass growth patterns of both MBRs were similar since the operating conditions were kept in the same ranges. Figure 51 and 52 illustrates the MLSS curves and MLVSS curves over the study period. The quick growth appeared in the first thirty days and then kept steady and sometimes fluctuated depending on the process conditions changes. The concentration ranges of MLSS and MLVSS in each stage were indicated in Table 20. The highest MLSS concentrations of both MBRs all occurred in stage III (HRT=4 hours) in membrane tanks. They were 9980 mg/L for MBR1 and 9680 mg/L for MBR2. Declines in MLSS concentrations were observed during periods around day 59 (MLSS=4700 mg/L for MBR1, MLSS=4880 mg/L for MBR2), and day 80 (MLSS=5050 mg/L for MBR1, MLSS=5000 mg/L for MBR2) when the wasting sludge rate was

increased to reduce foam. In the same study period, the average MLSS concentration of GBWWTP was between 1922 mg/L and 3774 mg/L. The MLSS growth curve was stabilized in a flat pattern. Figure 51 illustrates the average MLSS growth curves of aeration zones of both MBRs, as compared to the MLSS concentrations of the 4th path of aeration tank of GBWWTP over the study period.

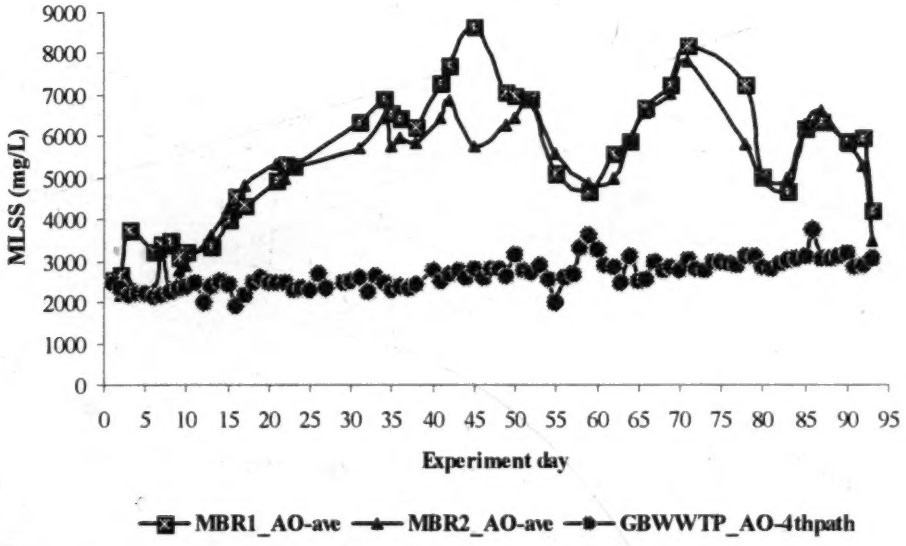

Figure 51. The average MLSS of MBR AO zones, as compared to the MLSS of the 4th of aeration tanks of GBWWTP full-scale BNR system over the study period.

The active biomass ratios of MLVSS to MLSS in MBR1 were between 68% to 81%, averaged 75% in aerobic zone of bioreactor, between 60% to 81%, averaged 74% in membrane tank. For MBR2 the active biomass ratios were between 47% to 82%, averaged 73% in AO zone of bioreactor, between 38% to 80%, averaged 73% in membrane tank. Although the MLSS concentrations in MBRs were much higher than that of GBWWTP, the active biomass ratios of both MBRs were quite consistent with that of

GBWWTP. Only slight variations occurred due to the changes of process operation conditions in MBRs. Figure 53 and 54 show the curves of the active biomass ratios of MLVSS / MLSS in both MBRs and GBWWTP.

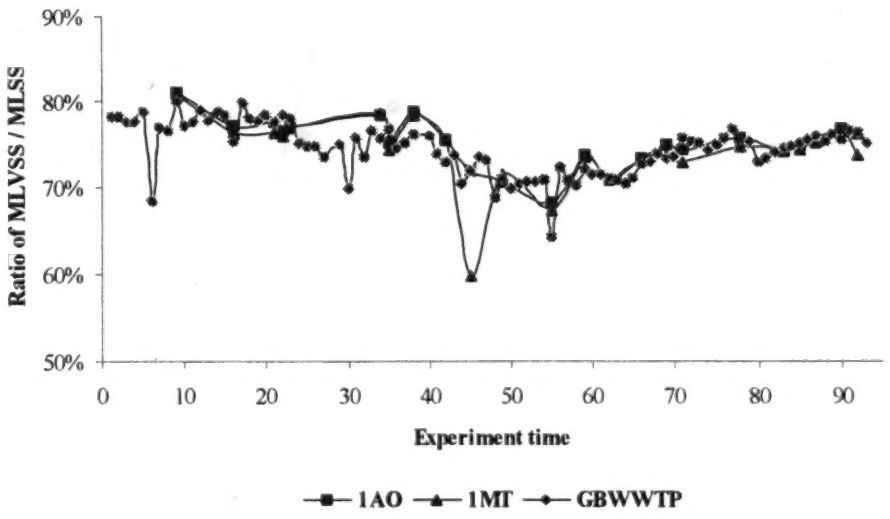

Figure 52. The ratio of MLVSS / MLSS in both aeration zone and membrane tank of MBR1, as compared to that of aeration tank of GBWWTP full-scale BNR system.

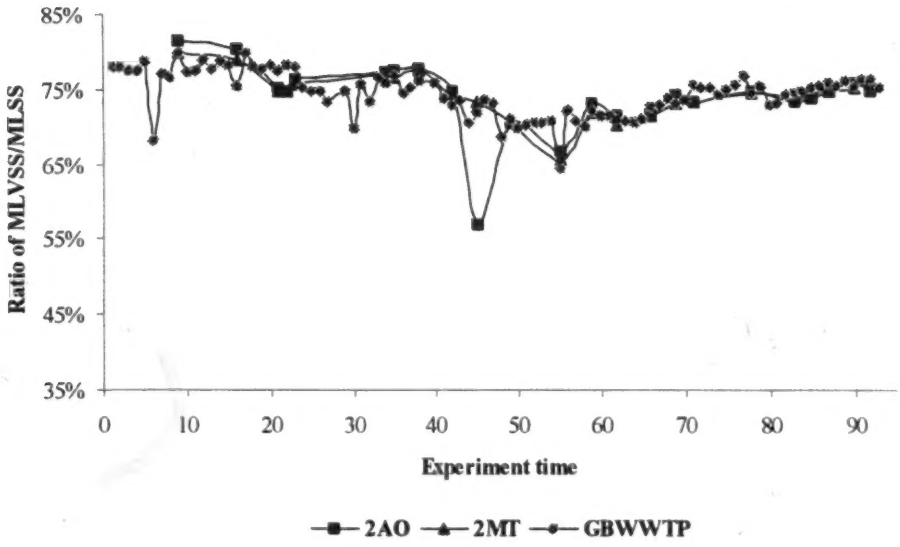

Figure 53. The ratio of MLVSS / MLSS in both aeration zone and membrane tank of MBR2, as compared with that of aeration tank of GBWWTP full-scale BNR system.

The active biomass ratio in MBR1 was slightly higher than that of MBR2. It was probably because that there was more returned sludge from aerobic zone to pre-anoxic zone. The active biomass ratios in both bioreactors and membrane tanks indicated slight overall decline patterns from about 80% to 75% over the 92 day study period. The declines were obvious during stage II (day 47 to 57) when the hydraulic loading was the least (HRT=8 hours) and less food supplies limited the growth of active biomass. In stage III, the active biomass ratios were slightly increased since the more food were supplied with a short HRT of 4 hours. But they were still slightly lower than that of stage I (HRT of 6 hours). It was probably due to the accumulation of inert inorganic solids in MBRs derived from the influent wastewater and cell debris from endogenous respiration.

Since there was sufficient mixing in both non-aeration zones and aeration zones, no significant sludge deposits were observed. However, some very small deposits attached to the sidewalls as well as the corners of the bioreactor cells and membrane tanks. Over the time these small deposits turned into black spots probably due to the fermentation. Secondary release of ortho-phosphate ($O\text{-}PO_4^{3-}$) was likely to occur after extended retention time of the deposits in MBRs. It may affect the stability of the system performance on biological phosphorus removal.

4.1.8 Food to Microorganism Ratio

One of important process parameters used for process designs and operations is the food to microorganism (biomass) ratio (F/M). Typical values for the BOD F/M ratio reported in the literature rang from 0.04 g substrate / (g biomass × day) for extended aeration process to 1.0 g / (g × d) for high rate aeration processes. Table 22 summarizes the typical design and operating parameters for commonly used activated-sludge processes.

Table 22. Typical parameters for common activated-sludge processes.

Process name	Flow pattern	SRT d	F/M kg BOD/ Kg MLVSS d	MLSS mg/L	HRT h
Extended aeration	Plug flow	20 to 40	0.04 to 0.10	2000 to 5000	20 to 30
Conventional plug flow	Plug flow	3 to 15	0.2 to 0.4	1000 to 3000	4 to 8
Complete Mix	CMAS	3 to 15	0.2 to 0.6	1500 to 4000	3 to 5
High-rate aeration	Plug flow	0.5 to 2	1.5 to 2.0	200 to 1000	1.5 to 3

Adapted from Metcalf and Eddy Inc. (2003).

The MBRs were operated at long SRTs of 14 to 19 days with relative high MLSS concentrations (4000 to 9000 mg/L). The F/M ratios of both MBRs were between 0.2 to 0.3 kg BOD/kg MLVSS day (Table 23). The ratios were in line with the typical F/M ratio

of conventional plug flow. But the MLSS concentrations of MBRs were much higher than that of conventional plug flow. With consideration of MLSS, the F/M ratios of MBRs seemed unexpected high, compared to that of conventional plug flow with low MLSS. The reason was that the BOD concentration in the PE feed was also higher than expected, which led to high BOD loading for MBRs. Reason of high BOD concentrations are discussed in later chapters.

Table 23. F/M ratios in different stages of MBR1 and MBR2.

Operation Stages	Average BOD load kg/day	MBR1 Average MLVSS kg	MBR1 F/M ratio kgBOD/ kg MLVSS day	MBR2 Average MLVSS kg	MBR2 F/M ratio kgBOD/ kg MLVSS day
HRT=6h	0.114	0.509	0.224	0.487	0.234
HRT=8h	0.101	0.479	0.211	0.448	0.225
HRT=4h	0.174	0.516	0.337	0.485	0.358

It was observed that the F/M ratio with the shortest HRT was the highest and the F/M ratio with the longest HRT was the lowest for both MBRs. It can be explained that the shortest HRT provided MBRs highest BOD load. The increase of the BOD load surpassed the increase of biomass (MLVSS) and led to higher F/M ratios.

4.1.9 VFA

Fermentation products assimilated by PAOs are normally represented by volatile fatty acids (VFA). VFA included acetic acid, propionic acid and buryic acid. VFA results indicated that MBR-PE-Feed was not productive of VFA. Almost all propionic acid and buryic acid were lower than detection limits. Only four samples out of 11 had higher

acetic acid concentrations than the detection limits (Figure 54). VFA profile for GBWWTP primary effluent indicates similar pattern (Figure 55).

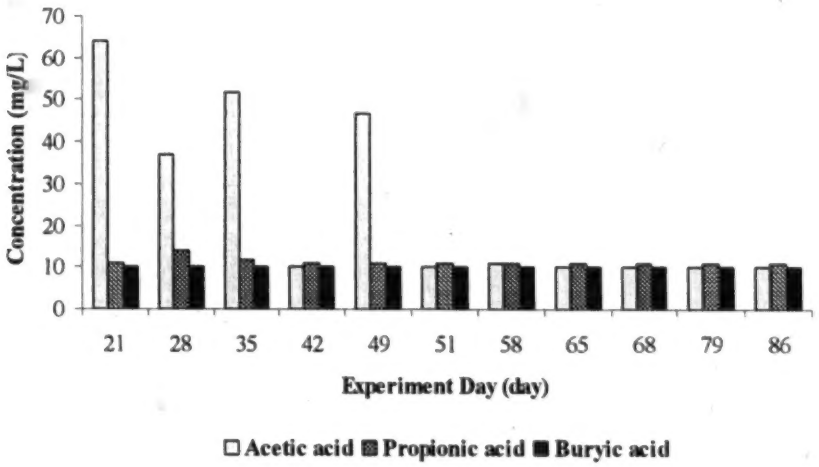

Figure 54. VFA profile for MBR-PE-Feed.

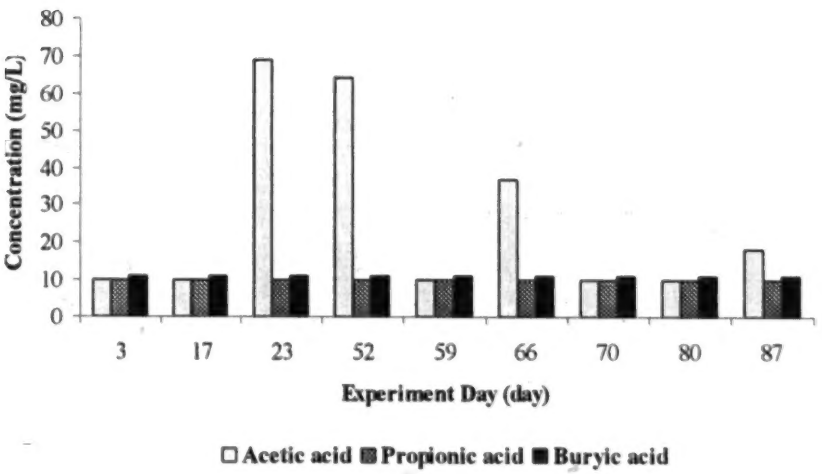

Figure 55. VFA profile for GBWWTP PE.

4.1.8 pH

In the beginning of the experiment (Day 1 to 16), it was found that the probe of the Acumet 950 pH meter used for pH measurement did not function well. The readings were unexpected high and fluctuated wildly. Therefore the data obtained during this period was not valid data. The Acumet 950 pH meter functioned correctly after the probe was replaced. Figure 56 illustrates the pH curves for MBR-feed and permeates from MBR1 and MBR2.

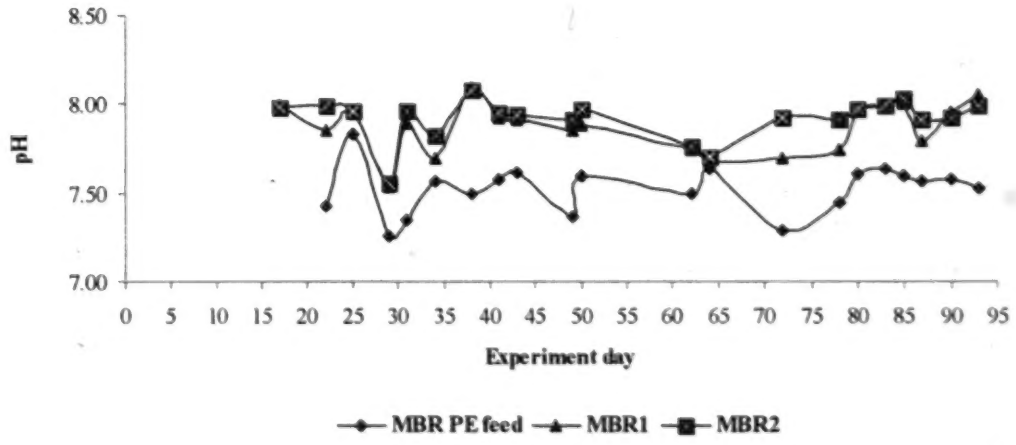

Figure 56. The pH curves for MBR-feed and permeates.

It was observed that the pH of MBR-feed, averaged 7.53 was lower than the pH of MBR permeates, averaged 7.87 and 7.92 for MBR1 and MBR2, respectively. The increase of alkalinity in permeates may lead to the increase of permeate pH due to denitrification. The pH range of MBR-feed to permeates was in line with the optimal pH range (7 to 8) required for biological nutrient removal.

4.1.10 Temperature

Figure 4.1.10 illustrates the comparison of MBR-feed temperature and GBWWTP raw influent during the study period. The temperature was fairly stable during the study period. MBR-feed temperature ranged from 10.5 °C to 14.6 °C and averaged 12.7 °C. It was consistent with the temperature of GBWWTP raw influent. The temperature difference between MBR aeration tanks and GBWWTP aeration tank was occasionally checked using a thermometer. The temperature of MBR aeration tanks was about 2 to 3 °C higher than that of GBWWTP aeration tank. This can be explained that MBR experiment was operated in the tunnel with higher environment temperature compared to the outside operation of GBWWTP aeration tank.

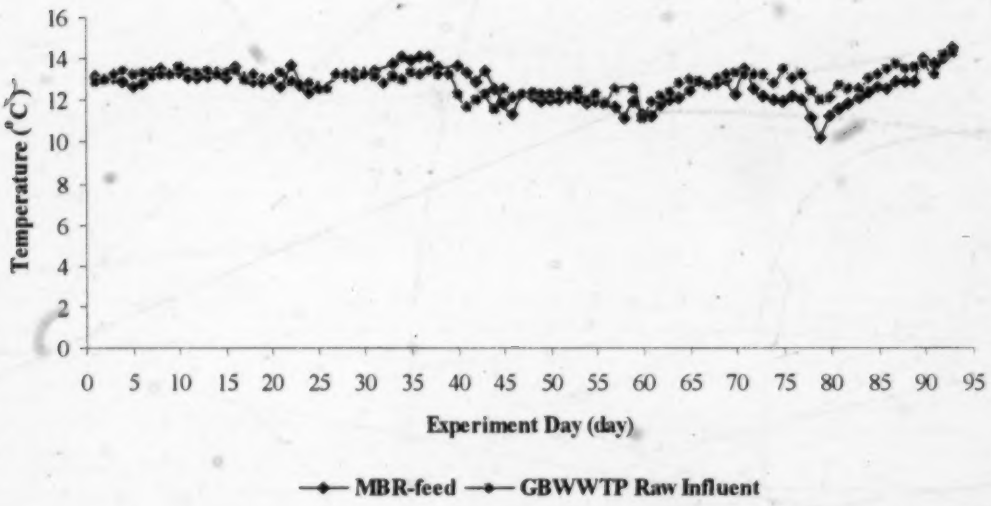

Figure 57. Temperature curves for MBR-PE-Feed and GBWWTP raw influent.

4.1.11 Membrane Performance

Both ZW-10 membrane modules used in the experiment worked well during the study period. W102046 used in MBR1 had a slight better performance than W102047 used in MBR2, in terms of the total coliform reduction (See later discussion of colifom reduction). The pressure transducer for MBR2 was in malfunction between day 13 to 76 due to unexpected reason. The reading range was shifted more from negative side to positive side. Therefore the monitoring of suction pressures and backpulse pressures relied more on MBR1 pressure transducer. It was observed that the operation range of suction pressure and backpulse pressure, as listed in Table 20, was fully in line with the normal operation range of ZW-10 (± 48 kPa). The suction pressure increase was more quickly with the short HRT of 4 hours. But both membrane modules functioned well in all three different HRT stages. The design flux rate (30 L/m^2h) was reached within good performance. Figure 58, 59 and 60 illustrate the production / backpulse patterns of three different stages for MBR1.

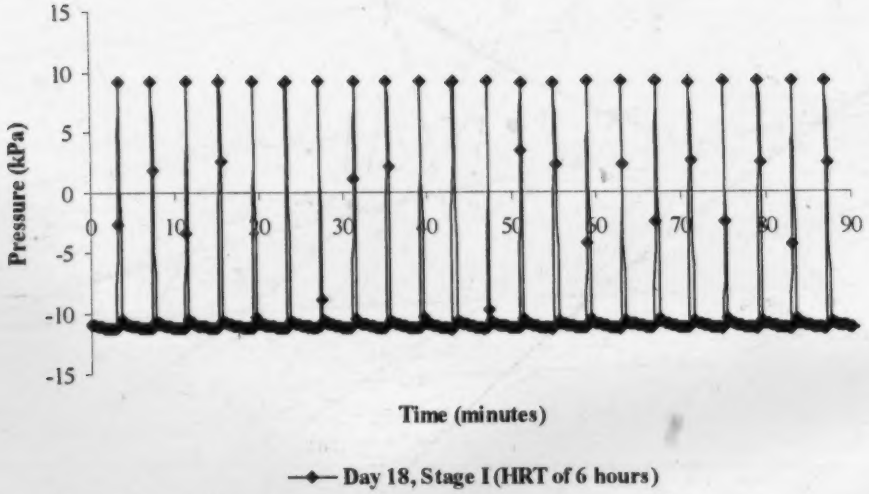

Figure 58. Production / backpulse pattern of stage I (HRT=6 hours, MBR1).

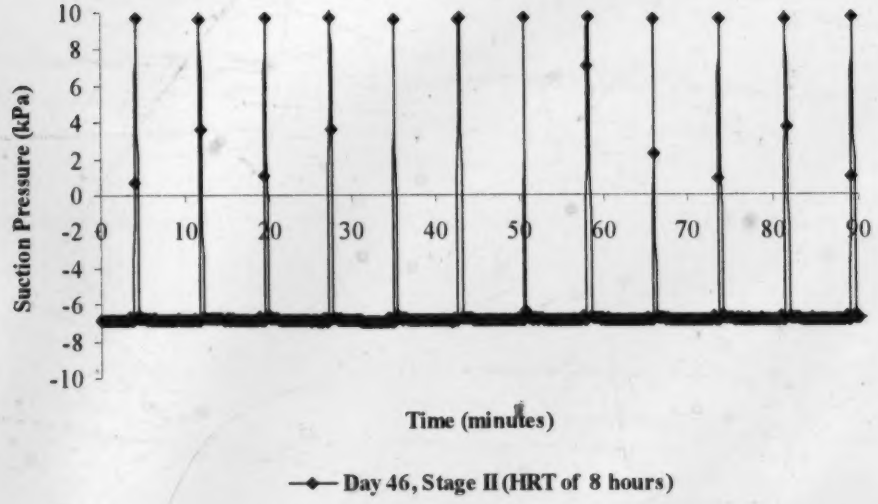

Figure 59. Production / backpulse pattern of stage II (HRT=8 hours, MBR1).

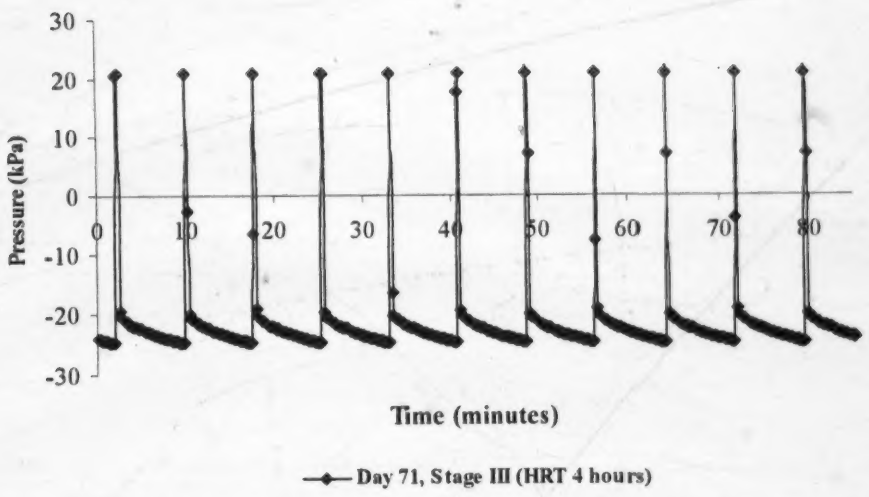

Figure 60. Production / backpulse pattern for stage III (HRT=4 hours, MBR1).

The position of pressure transducer was installed about 70 to 100 mm above the mixed liquor level through a stainless steel tube. A 100 mm high water could produce about 0.7 kPa pressure. According to the transmembrane pressure (TMP) equation, the suction pressure was about 0.7 kPa higher than transmembrane pressure. If the difference is neglected, the suction pressure is equal to TMP.

4.1.12 Membrane Fouling Control

In the study, membrane fouling was controlled by a periodically backpulse. The MBR systems were designed for both maximum suction pressure backpulse and periodical backpulse. The maximum suction pressure was set for –48 kPa. When the suction pressure reaches –48 kPa, the permeate pump will turn into opposite direction for backpulse. But since the suction pressure never reached –48 kPa, the maximum suction pressure backpulse was never activated during the study.

The MBR systems were always operated with periodical backpulse. The time ratio can be inputted into the control software and can be changed at any time without stopping the systems. The ratio of production/backpulse ranged from 450 s / 15 s to 125 s / 8 s. The production/backpulse was mostly running at 450 s / 15 s. 225 s / 15 s and 125 s / 8 s were only occasionally applied when the membrane suction pressure increased quickly. The membrane fouling was indicated by an increase of suction pressure. For a 32-day operation of HRT 6 hours, the average suction pressure was slightly increased from -9.5 kPa to -11.2 kPa. For a 35-day operation of HRT 4 hours, the average suction pressure was increased from -14.2 kPa to -26.6 kPa. As the study was carried out within limited period and suction pressure increases in the operation stages were not substantial, production/backpulse was sufficient for membrane fouling control. Therefore no chemical cleaning was involved in the operation. Both membrane modules were operated continuously through the entire study period. No significant deposits or biofilms were visually observed on membrane fibres when the experiment was completed and the membrane tanks were drain out.

4.1.13 Foaming Control

No foaming was observed during the operation of startup and stage I of HRT 6 hours (Day 1 to day 45). Very slight foaming occurred in some aerobic cells of MBR1 on day 48, three days after the operation condition was changed from stage I of HRT 6 hours to stage II of HRT 8 hours. This may be explained that the hydraulic loading decrease led to less food supplies to microorganisms and promoted the growth of filamentous organisms.

The activated sludge was checked on day 55 by GBWWTP laboratory under microscopes. Low filamentous activities and protozoa activities were observed. No worms and rotifers were found. From day 56 to 57, both MBR systems were shutdown for about 17 hours due to GBWWTP PE line out of service. More foaming appeared during the system shutdown. A temporary PE line was connected from the PE channel of GBWWTP No.2 tank to the MBR site and both MBR systems started on a new operating condition (stage III) of HRT 4 hours on day 57. Overall foaming was reduced after the restart of the operation under a higher hydraulic loading. On day 71, more foaming accumulated and appeared for the first time in all aerobic cells except for membrane tanks in both MBRs. The aeration for MBR2 was increased from 2.0 m^3/h to 5.7 m^3/h for about half an hour to check if the foam could be reduced. The foaming was not decreased and became severe. On day 75, for the first time thick foaming occurred and covered to each AO cell except for membrane tanks. The foam was manually cleaned out. But it rose quickly again after the cleaning up.

On day 78, the waste sludge flow rate was increased from 4 mL/min to 16 mL/min to reduce solids and hopefully to reduce the foaming. By increasing the waste sludge rate, 12 mL/min more PE feed was supplied to each MBR system, in the meantime, the biomass was reduced by higher WS rate. With more food entering the systems and less biomass, an unfavorable condition for filamentous microorganisms to grow resulted, which led to a decrease of foaming. On day 81, the foaming was greatly reduced and on day 83, only some slight foam still appeared in some aerobic cells and the WS rate was

reduced back to 4 mL/min. On day 85, foaming was almost removed. Reducing solids was an effective way to control foaming. But it was also observed that once the foaming occurred, it was hard to remove the residual filamentous microorganisms completely since the solids could not be reduced to an unacceptable level, which would largely affect the performance of the systems.

4.1.14 Operation Troubles & Solutions

Both MBRs performed well during the 92 day study period. However, some difficulties were also encountered during the operation. Table 24 summarizes the major difficulties occurred in the experiment.

4.1.15 Operation Data Log

All online monitoring data were automatically logged into the excel file and stored in computer on a daily basis. These online data included feed temperature, production/backpulse pressure and dissolved oxygen. These operation data files were copied and backed up periodically. The operation events and analysis results were manually recorded in lab notebook. Summary of major operation events was included in Appendix C.

Table 24. Operation troubles and counter measures.

Major difficulties	Time	Causes	Counter measures
Shutdown 1	22 hours (day 22 to 23)	GBWWTP PE line blocked	Air (120 psi) to blow through
Shutdown 2	3 hours (day 32)	Power failure by GBWWTP	Restarted computer
Shutdown 3	15 hours (day 38 to 39)	Power failure by GBWWTP	Sealed power supply box and ensured the GBWWTP operator not turn off the power
Shutdown 4	17 hours (day 56 to 57	GBWWTP PE line out of service	Built a temporary PE line.
Foaming	Day 71 to 85	Hydraulic loading changes, shutdowns or PE feed characteristics changes	Increased WS rate and reduced solids
Transducer #2 malfunction	Day 13 to 76	unknown	Reference to #1 for monitoring
Mixed liquor backflow to feed tank	Occasionally	R3 pump tubing replaced and restarted, mixed liquor level raised quickly	Slowly increased the pump rate when started
Tubing narrowed or blocked	Occasionally	Solids accumulated or large sludge flocs in later experiment period	Manually shook or cleaned up the tubing

4.2 MBR Profiling

4.2.1 MBR Reactor Profiling

A MBR reactor profile analysis was carried out once a week. Five mixed liquor samples were withdrawn from MBR1, which included pre-anoxic zone, anaerobic zone, anoxic zone, aerobic zone and membrane tank. Four mixed liquor samples were taken from MBR2, which included anaerobic, anoxic, aerobic zones and membrane tank. The mixed

liquor samples were first processed by centrifuge to get the supernatant, then the supernatant was filtered by 0.45 μm membrane. The filtrate was used to perform the profile analyses of COD, NH_3-N, TOX-N and PO_4^{3-}-P. The series tests were normally completed within one day, on every Thursday. GBWWTP provided the laboratory facilities. Some reagents necessary for the tests were supplied by University of Alberta. All the profile analyses were carried out by the research student.

The same mixed liquor samples were also taken once a week for solids profile analysis. The samples were sent to GBWWTP laboratory and GBWWTP laboratory carried out the MLSS and MLVSS profile analyses each time, normally on every Tuesday.

4.2.1.1 Mixed Liquor Suspended Solids Profile Analysis

Mixed liquor suspended solids (MLSS) included biomass, cell debris, non-biodegradable volatile suspended solids (nbVSS), and inert inorganic total suspended solids. The portion of biomass, cell debris and nbVSS are also commonly termed as mixed liquor volatile suspended solids (MLVSS). The results of solids profile analysis represent the distribution of the biomass in the MBR reactor.

It was observed that solids concentrations (MLSS and MLVSS) in membrane tanks was always the highest concentration. MLSS and MLVSS concentrations increased along the MBR reactor from non-aeration zones to membrane tank. During the operation, the solids were continuously rejected by the membrane and stayed in membrane tank while permeate was withdrawn by permeate pump. The accumulated solids ultimately caused

the increase of solids concentrations in membrane tank until a dynamic mass balance was maintained by certain rates of sludge wasting and recirculation. The solids concentrations in other zones were dependent on the growth characteristics of microorganisms in different zones and the recirculation rates from either membrane tank or aerobic zone. Table 25 summarizes the ratio of solids concentrations in different zones to membrane tank for MBR1 and MBR2. It also presents the ratio of the average solids concentration of each MBR to MLSS concentration of its membrane tank.

Table 25. Ratios of mixed liquor solids concentrations in each zone, as compared to that of membrane tanks for both MBR1 and MBR2.

Mixed liquor solids	MBRs	Xpr/Xmt*	Xae/Xmt*	Xan/Xmt*	Xao/Xmt*	Xave/Xmt*
MLSS	MBR1	49.4%	48.4%	71.9%	81.5%	79.3%
MLSS	MBR2	-	37.8%	66.7%	83.2%	78.9%
MLVSS	MBR1	52.1%	52.0%	73.3%	82.9%	80.1%
MLVSS	MBR2	-	41.9%	68.3%	84.9%	79.7%

*X: Solids concentration
*pr: pre-anoxic, ae: anaerobic, an: anoxic, ao: aerobic zone. mt: membrane tank.
*ave: MBR average solids concentration over all zones and membrane tank

Figure 61 and 62 illustrate the solids distributions along each zone and membrane tanks. The solid concentrations were tested by GBWWTP laboratory with single measurement analysis for each sample.

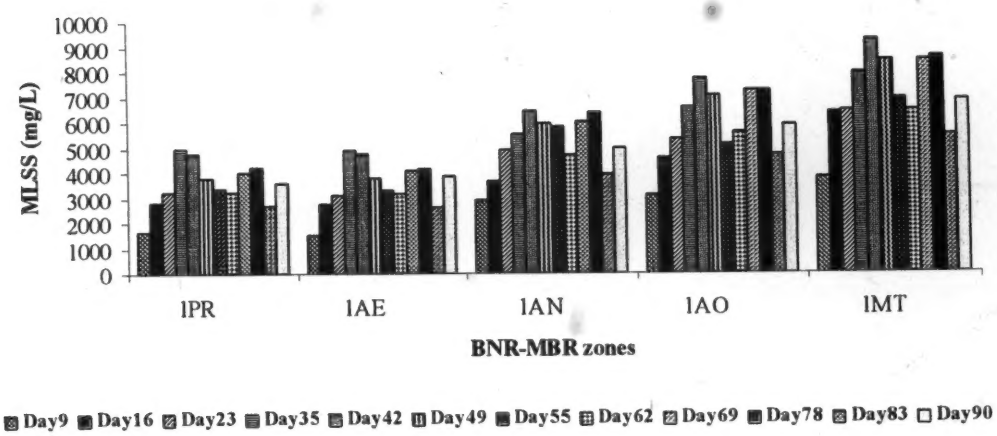

Figure 61. MLSS distribution for MBR1.

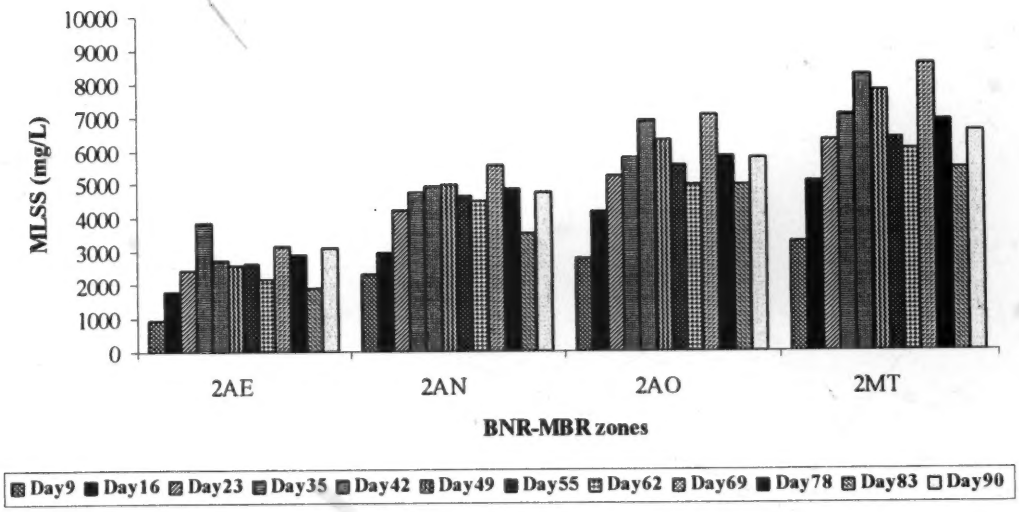

Figure 62. MLSS distribution for MBR2.

It was also observed that the percentage of MLVSS to MLSS decreased along each MBR reactor, which was opposite to the increasing trend of solids concentrations. This can be

explained that more membrane rejected inert solids (inorganic matter) accumulated along the MBR reactor with recirculations. Figure 63 shows the ratio (MLVSS / MLSS) distribution along the MBR reactor.

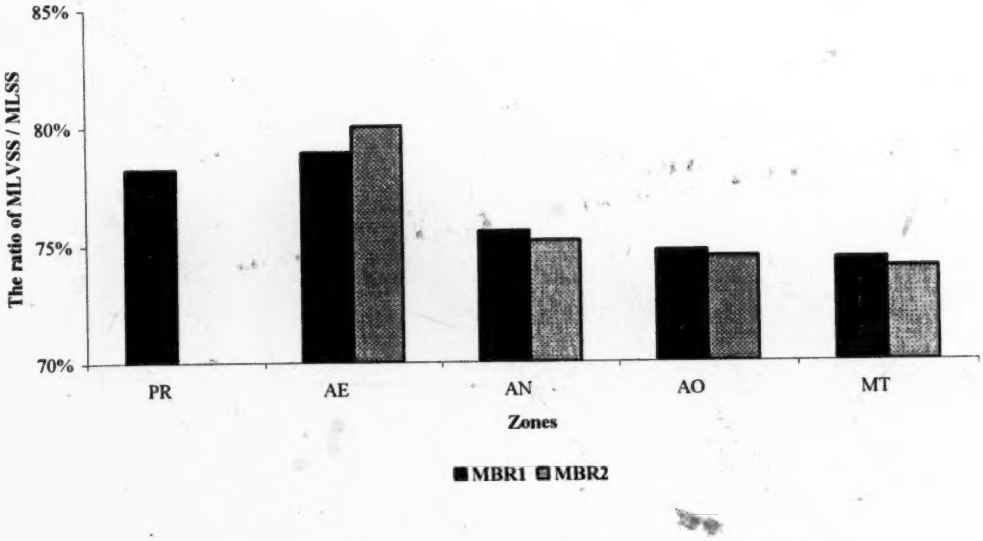

Figure 63. The distribution of the MLVSS / MLSS ratio in MBRs.

4.2.1.2 Soluble COD Profile Analyses

As mentioned in section 3.5.5, soluble COD (sCOD) profile analyses were performed using *Standard Methods* 5220 D /HACH #8000 from day 23 to day 86. COD tests were done on the mixed liquor filtrate through a 0.45 μm membrane filter. The sCOD contains readily biodegradable COD, a small fraction of the colloidal COD and non-biodegradable soluble COD (nbsCOD). The purpose of the sCOD profiling tests was to find out how the readily biodegradable organic substrate (rbCOD) was consumed along each zone of

MBRs. Figure 64 and 65 illustrate the soluble COD (sCOD) profile along MBR reactors. It was expected that sCOD decreased as the flow went through the non-aeration zones, aerobic zone and membrane tank. But the profiling results indicated that sCOD steadily increased along the reactor from the non-aeration zones to membrane tank.

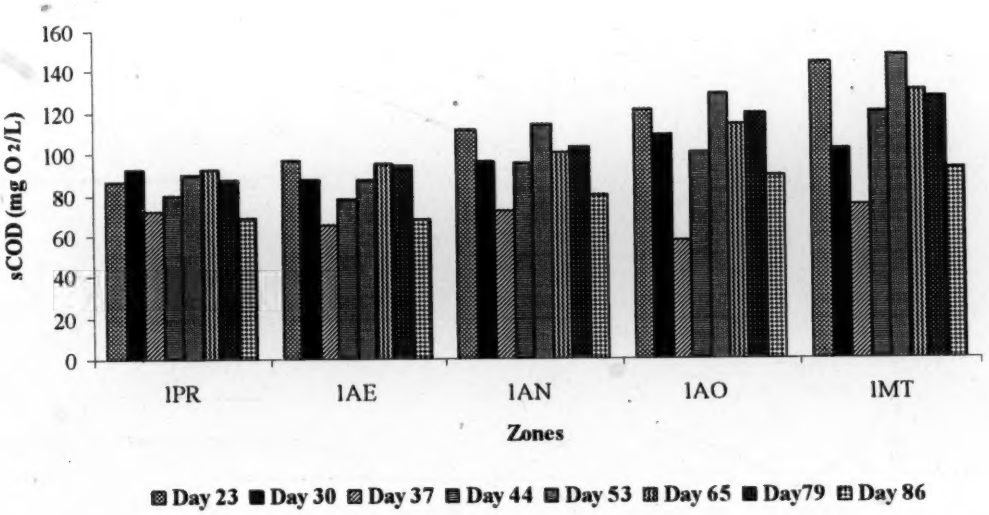

Figure 64. The sCOD profile of MBR1.

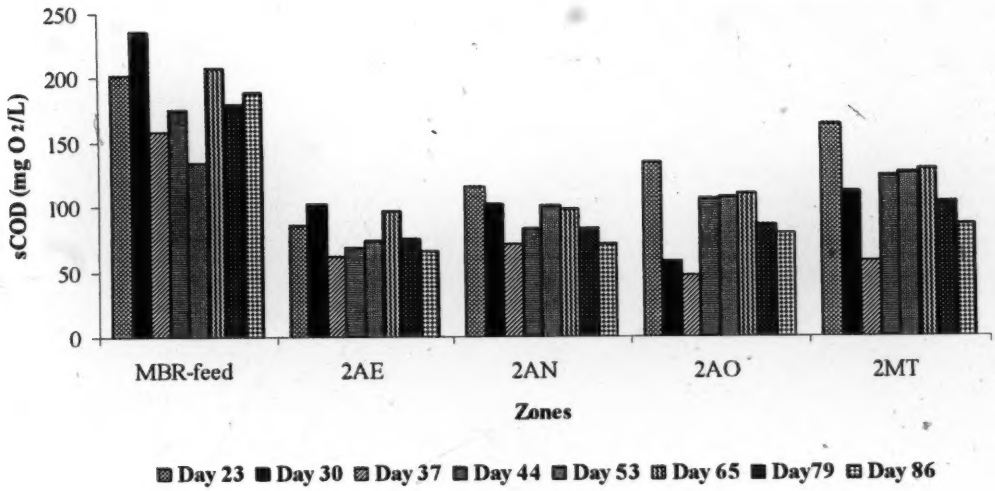

Figure 65. The sCOD profile of MBR2.

Table 26 and 27 outline the average sCOD results of MBR-feed and the average COD of the mixed liquor along each zone of MBRs. The sCOD in MBR-feed decreased 55% in pre-anoxic zone for MBR1 and 58% in anaerobic zone for MBR2. Then sCOD started to increase, compared to sCOD in pre-anoxic zone and anaerobic zone. sCOD in anoxic zones increased 15% for both MBRs, sCOD in aerobic zones increased 25% for MBR1 and 16% for MBR2. COD in membrane tank increased 40% for MBR1 and 43% for MBR2.

One of the thoughts for sCOD increasing along the MLSS concentrations was that centrifuge might lead to bacteria decomposition and hydrolysis and ultimately to the increase of sCOD. Therefore, on day 86, the mixed liquor samples for profile analyses were not treated by centrifuge. A paper filtration was used for pretreatment of all profile

samples prior to the filtration by 0.45 μm membrane filter. The COD results on these samples showed the same increase trend along the MBR reactor although the COD values were lower than average sCOD in each zone of MBRs. It indicated that centrifuge pretreatment was not the cause for the COD increase. The other explanation was that with high MLSS concentrations, many particles including cell debris, organic and inorganic matters, were broken up during the bioreactions and dissolved in water along the reactor. These dissolved matters were small enough to pass through 0.45μm membrane filter and resulted in high sCOD in line with high MLSS along the MBR reactor. The higher the MLSS concentration, the higher the soluble COD. Wentzel *et al.* (1989) indicated that nonbiodegradable soluble COD may generated from the endogenous respiration.

The COD profiling tests indicated that to get a full picture of readily biodegradable COD (rbCOD) consumption along each zone of MBR reactor was not practical through 0.45μm membrane filter. A smaller pore size filter may be tested for further improvement.

Table 26. The average sCOD* distribution along MBR1 reactor.

Zone	1PR	1AE	1AN	1AO	1MT
Unit	COD mg/L	COD mg/L	COD mg/L	COD mg/L	COD mg/L
Mean	83	84	96	105	117
STDEV	9	12	14	23	25
Max	92	97	114	129	147
Min	68	65	72	57	75
Samples	8	8	8	8	8

* 0.45 μm filtered samples.

Table 27. The average COD* distribution along MBR2 reactor.

Zone	MBR-feed	2AE	2AN	2AO	2MT
Unit	COD mg/L	COD mg/L	COD mg/L	COD mg/L	COD mg/L
Mean	185	78	90	90	112
STDEV	31	15	16	29	32
Max	236	102	115	134	163
Min	134	62	71	47	57
Samples	8	8	8	8	8

* 0.45 μm filtered samples

4.2.1.3 NH_3-N Profile Analysis

Ammonia nitrogen profiling tests for mixed liquor in MBR reactor were performed using a quick method/HACH DR/4000: Nessler HACH method 8038 adapted from *Standard Methods* 4500-NH3 B & C. It was observed that the concentration of NH_3-N decreased along the MBR reactor. Figures 66 and 67 illustrate the average NH_3-N distribution for MBR1 and MBR2, respectively.

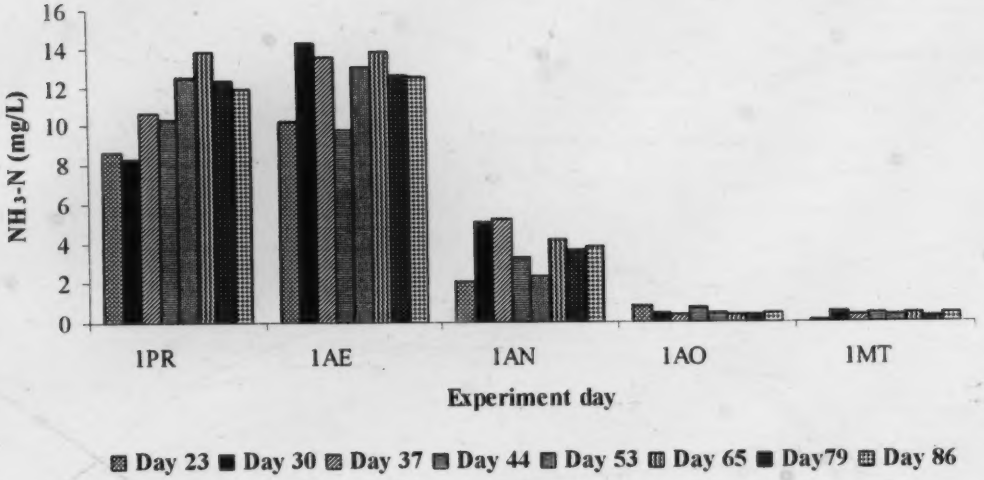

Figure 66. The NH_3-N profile of MBR1

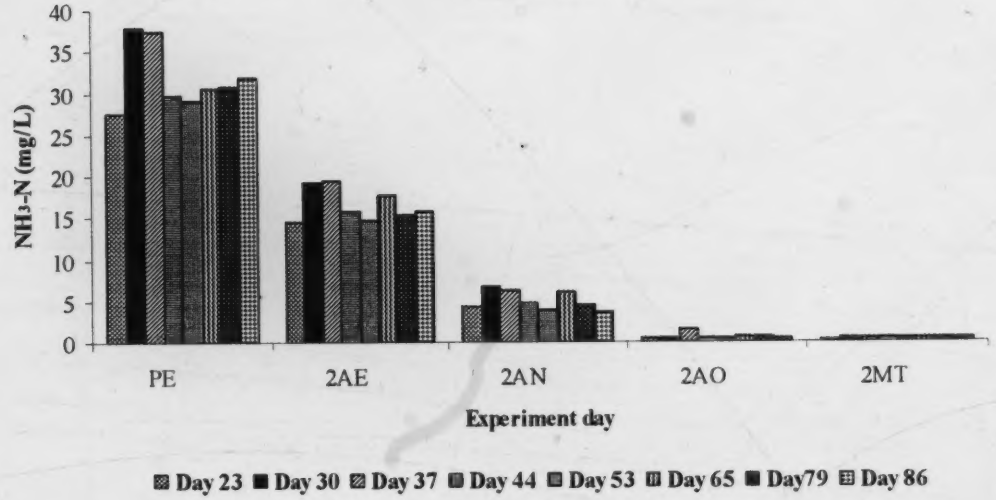

Figure 67. The NH_3-N profile of MBR2

Tables 28 and 29 summarize the average NH_3-N concentrations of MBR-feed and of each zone of MBRs. The average NH_3-N concentrations decreased 65% in pre-anoxic zone for

MBR1 and 48% in anaerobic zone for MBR2. This can be explained that the NH_3-N concentration was immediately diluted after the feed entering the MBR bioreactor and besides, nitrification probably also occurred in pre-anoxic zone and anaerobic zone due to high DO presented in returned mixed liquor. The returned mixed liquor (R1-MBR1) from aerobic zone (the last cell) to pre-anoxic zone (the first cell) in MBR1 contained higher DO concentrations than that of the returned mixed liquor (R1-MBR2) from the backend of anoxic zone to anaerobic zone. The higher DO in returned mixed liquor led to the higher reduction (65%) of NH_3-N in pre-anoxic zone of MBR1. Some ammonia might be assimilated into organic nitrogen (bacteria cells) and resulted in the reduction of NH_3-N.

After pre-anoxic zone, the NH_3-N recovered from 65% reduction to 61% reduction in subsequent anaerobic zone in MBR1. It indicated that the DO and nitrate in pre-anoxic zone were completely consumed and ammonia nitrogen derived from bacteria decomposition and hydrolysis in anaerobic zone led to the decrease of NH_3-N reduction.

It was very interested to observe that most of ammonia reduction was completed even before aerobic zone. In the anoxic zones NH_3-N reduction reached 89% in MBR1 and 84% in MBR2. It was suspected that nitrification and denitrification simultaneously occurred in anoxic zones. After anoxic zones, NH_3-N reduction in MBR1 reached 98% in aerobic zone, 99% in membrane tank. NH_3-N reduction in MBR2 reached 99% in both aerobic and membrane tank.

Table 28. The average NH_3-N distribution of MBR1.

MBR1	1PR	1AE	1AN	1AO	1MT
Unit	NH_3-N mg/L	NH_3-N mg/L	NH_3-N mg/L	NH_3-N mg/L	NH_3-N mg/L
Mean	11.0	12.5	3.7	0.5	0.4
STDEV	1.9	1.7	1.1	0.2	0.1
Max	13.8	14.3	5.2	0.8	0.5
Min	8.3	9.7	2.0	0.3	0.1
Samples	8	8	8	8	8

Table 29. The average NH_3-N distribution of MBR2.

MBR2	MBR-feed	2AE	2AN	2AO	2MT
Unit	NH_3-N mg/L	NH_3-N mg/L	NH_3-N mg/L	NH_3-N mg/L	NH_3-N mg/L
Mean	31.9	16.5	5.0	0.6	0.4
STDEV	3.8	2.0	1.1	0.4	0.1
Max	37.9	19.3	6.7	1.6	0.5
Min	27.6	14.4	3.7	0.3	0.3
Samples	8	8	8	8	8

4.2.1.4 NO_3^--N Profile Analysis

Nitrate nitrogen (NO_3^--N) profile tests were carried out from day 23 to day 86. Permeate samples were also included in the profile tests to get some comparison reference except for day 23 and 37 samples. Nitrate Electrode Method (4500- NO_3^- D) was used for nitrate nitrogen profile tests from day 23 to day 65. It was found that the NO_3^--N readings of mixed liquor samples fluctuated frequently and hardly stabilized. Therefore the nitrate electrode method was changed to Ion Chromatographic Method (St. Methods 4500- NO_3^- C) on day 79 and day 86 samples. Figures 68 and 69 illustrate the NO_3^--N profile results for both MBR reactors.

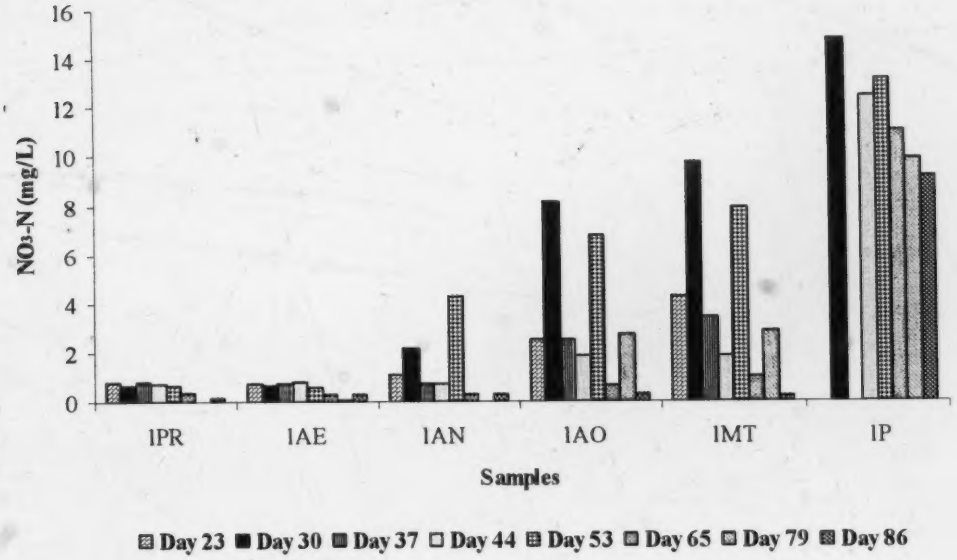

Figure 68. The NO_3^--N profile of MBR1.

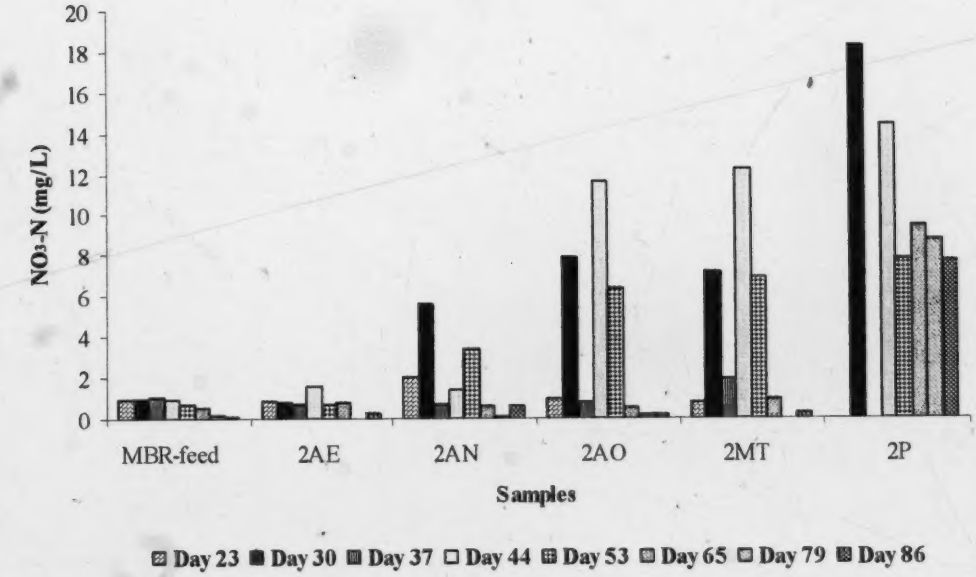

Figure 69. The NO_3^--N profile of MBR2

The NO_3^--N concentrations averaged 11.73 mg/L in MBR1 permeate and 11.04 mg/L in MBR2 permeate, which were much higher than that of mixed liquor samples in membrane tanks, averaged 3.99 for MBR1 and 3.77 for MBR2. Since permeates were obtained through 0.04 μm pore size membrane in membrane tanks and profile samples were also taken from membrane tanks, and the mixed liquor samples were filtered through 0.45 μm membrane filter for nitrate electrode method and 0.2 μm filter for IC method, it was expected that the NO_3^--N concentrations in mixed liquor profile samples from membrane tanks should be no less than that of permeates. From Figures 68 and 69, it was clearly observed that inconsistence between permeate and mixed liquor sample results and results variations among the same zone profile samples. This can be explained that a strong interference occurred during NO_3^--N tests for mixed liquor filtrate samples. It was most probably caused by some impurity matters passed through 0.45μm or 0.2μm filters, which interfered the electrode for the NO_3^--N tests.

To further prove the interference of mixed liquor samples, profile samples of day 86 included two deionized water (DI) blank samples. One of the DI blank samples was also filtered through paper filter as other mixed liquor samples did for pretreatment. This filtered DI blank was used to determine the potential NO_3^--N contamination by paper filter. The NO_3^--N profile analyses of a complete set of samples for both MBRs are illustrated in Figure 70. Most profile samples were below 0.3 mg/L NO_3^--N, which were contradicted to ammonia reduction results. Both permeates were between 7 to 9 mg/L NO_3^--N, which were in line with the TOXN results of routine permeate samples. The

filtered DI blank sample was at 0.14 mg/L NO_3^--N, which indicated a very slight NO_3^--N contamination, compared to 0.02 mg/L NO_3^--N of non-filtered DI blank sample. Both nitrate electrode method and IC method were probably not suitable for NO_3^--N tests of mixed liquor samples. A more reliable method is required for NO_3^--N profile analyses of mixed liquor samples.

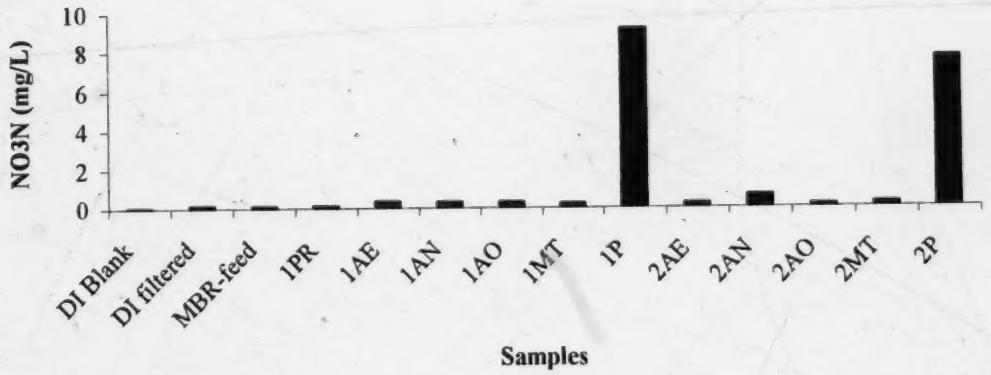

Figure 70. The NO_3^--N profile results on Day 86 (IC method)

4.2.1.5 PO_4^{3-}-P Profile Analysis

A quick method (Ascorbic Acid HACH method 8048) was used to determine the ortho-phosphate phosphorus (PO_4^{3-}-P) of mixed liquor profile samples. Figure 71 illustrates the PO_4^{3-}-P distribution along both MBR reactors.

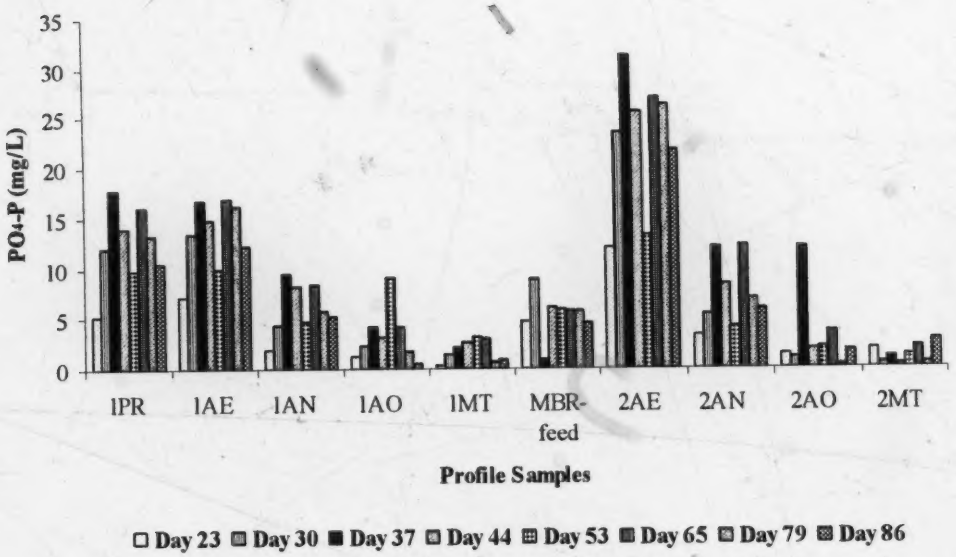

Figure 71. The PO_4^{3-}-P profile analysis results for both MBRs.

Due to phosphorus release, PO_4^{3-}-P concentrations increased 131% in pre-anoxic zone and 152% in anaerobic zone of MBR1, compared to the PO_4^{3-}-P concentration in MBR-feed. In MBR2, PO_4^{3-}-P concentration increased 325% in anaerobic zone, which was much higher than that of MBR1. This can be explained that the returned mixed liquor in MBR2 from the anoxic zone to the anaerobic zone (R1 of MBR2) contained less nitrate and dissolved oxygen than that in R1 of MBR1. The environment condition in anaerobic zone of MBR2 was more favorable for the growth of phosphorus accumulating organisms (PAOs) than that of MBR1. PAOs in MBR2 consumed more biodegradable soluble COD (bsCOD) and produced more intracellular polyhydroxyburtyrate (PHB). Concurrent with more bsCOD uptake in MBR2 is the release of more orthophosphate ($O\text{-}PO_4^{3-}$), which ultimately resulted in high PO_4^{3-}-P concentrations in anaerobic zone of MBR2.

Although PO_4^{3-}-P concentrations in both anoxic zones were still slightly higher than that of MBR-feed, PO_4^{3-}-P concentrations were largely reduced, compared to PO_4^{3-}-P concentrations in both anaerobic zones. It was probably because phosphorus uptake occurred in both anoxic zones due to the excess dissolved oxygen. After anoxic zones, PO_4^{3-}-P concentrations further reduced to 38% and 43% in aerobic zones, 67% and 75% in membrane tanks, respectively, for MBR1 and MBR1. PO_4^{3-}-P reduction was higher in MBR2 than MBR1. This can be explained that more PO_4^{3-}-P release in MBR2 anaerobic zone led to more PHB storage in PAO cells, which further resulted in more energy provided from PHB oxidation in aerobic zones and membrane tanks to form polyphosphate bonds in cell growth, and ultimately reduced PO_4^{3-}-P concentrations from solution. Permeate routine analyses for total phosphorus also proved that MBR2 had better performance for biological phosphorus removal than MBR1 (see section 4.3.10).

4.2.2 ASA Analysis

A complete activated sludge analysis (ASA) for both MBRs was performed by GBWWTP laboratory on the last day of the experiment (day 93). The ASA samples were withdrawn from membrane tank of MBR1 (1MT) and of MBR2 (2MT), respectively. The ASA results for both MBRs are summarized in Table 30.

Table 30. The ASA analytical results for MBR1 and MBR2.

Analytical items	Unit	1MT042904	2MT042904
MLSS	mg/L	7770	6852
MLVSS	mg/L	5754	5024
SSVI	mg/L	No settling	Very little settling (5%)
SOCR	mg O_2/h/g VSS	8	9
Rotifers	%	0	0
Primary filament ID		Microthrix parvicella	Microthrix parvicella
Primary filament	%	55	60
Secondary filament ID		Type 0041	Type 0041
Secondary filament	%	30	20
Networking of primary filament		No	No
Total filamentous length (TFL)	cm/mg VSS	4779	6529
Floc structure		Open	Partially Closed (50%)
Floc size		Large	Large
Protozoa activity		High	High
Supernatant		No supernatant	No supernatant

In conventional full-scale BNR activated sludge systems, some important properties of well working activated sludge are listed in Table 31.

Table 31. Some properties of well working activated sludge.

Activated Sludge Properties	Typical Rang
SSVI:	150 to 250 mg/g
SOCR:	5 to 10 mg O_2/h/g VSS
Protozoan:	Amoebic < 10%
	Flagellate < 10%
	Free-swimming 40 to 60%
	Stalked Cilliates 20 to 40%
Rotifers:	< 5%
TFL:	4000 to 8000 cm/mg VSS

Filamentous Identification	Possible Causes
-*Thiothrix app., Beggiatoa spp.*, Type 021N	Septic wastewater, sulfide indicator
-*N. limicola, M. parvicella, Nocardia spp.*, Type 0041, 021N, 0961, 0803, 1851	Low F/M ratio
Type 021N, *S. natans*, Type 1701	Low DO; short sludge age
-*M. parvicella*	Low temperature; increased VFA conc.
-*Nocardia spp., M. parvicella*	Long sludge age
-Type 1863, *Nocardia spp., M. parvicella*	Foaming organism

Note: adapted from GBWWTP ASA report

Compared to well working activated sludge in full scale BNR systems, ASA results for MBRs indicated that most MBR sludge properties, such as SOCR, protozoa activity, rotifers and TFL, were in line with the practical range of good sludge in GBWWTP full scale BNR systems. Figure 72 to 75 illustrate the structure of MBR sludge flocs at 10× magnification. As foaming occurred in the late period of the experiment (Figure 76), primary filamentous bacteria in the sludge were identified as *Microthrix parvicella*, which was probably caused by low F/M ratio, long sludge age and low temperature. Since the wastewater characteristic was hardly to change, the most effective way of controlling *M. parvicella* was to increase a waste rate of the activated sludge.

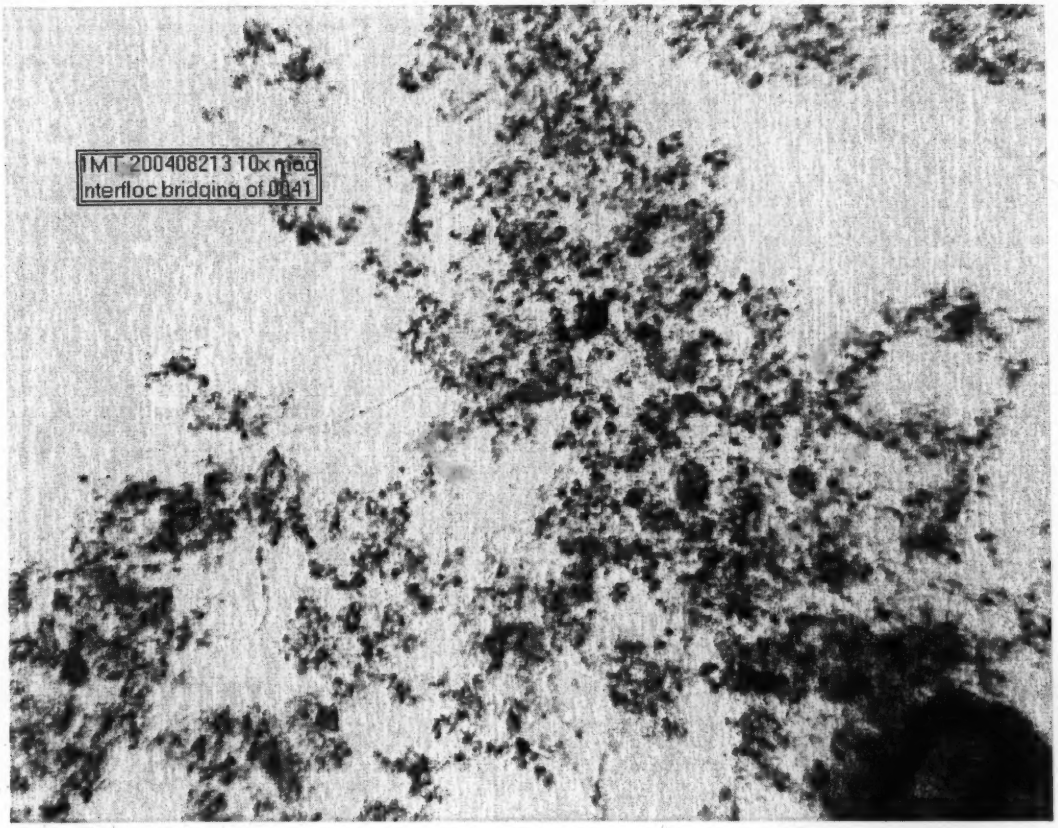

Figure 72. Interfloc bridging of 0041 @10×mag for 1MT sludge.

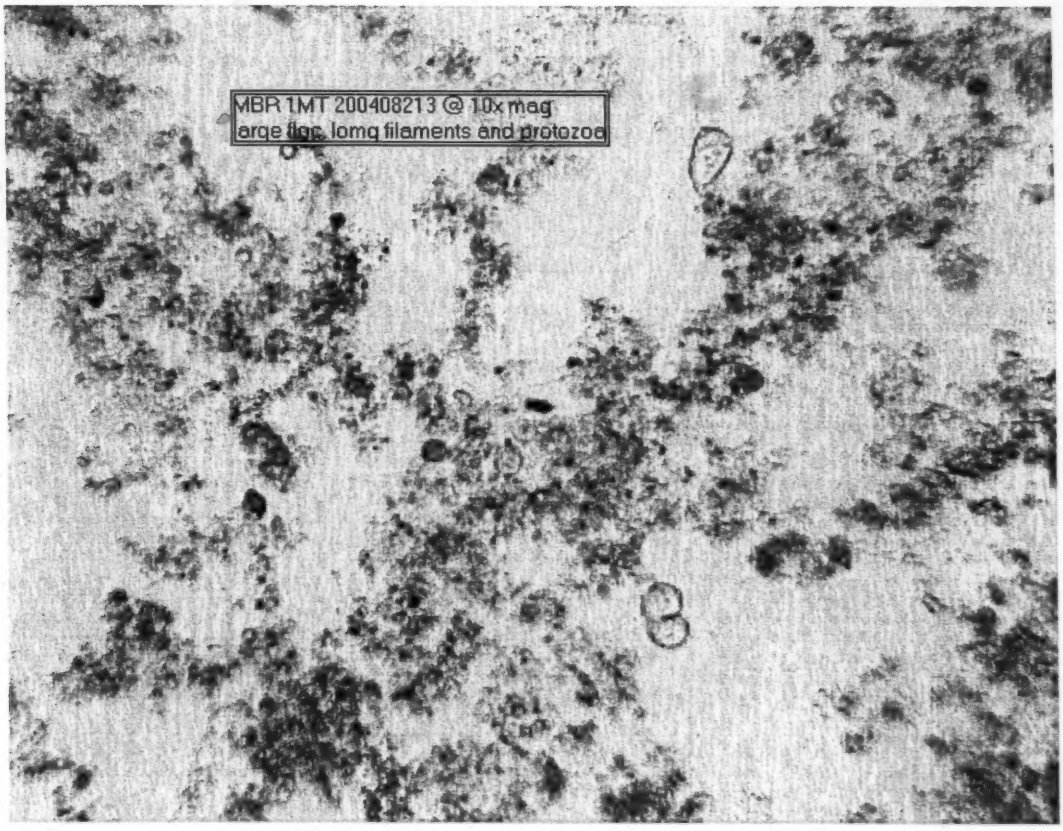

Figure 73. Large floc, long filaments and protozoa @10×mag for 1 MT sludge.

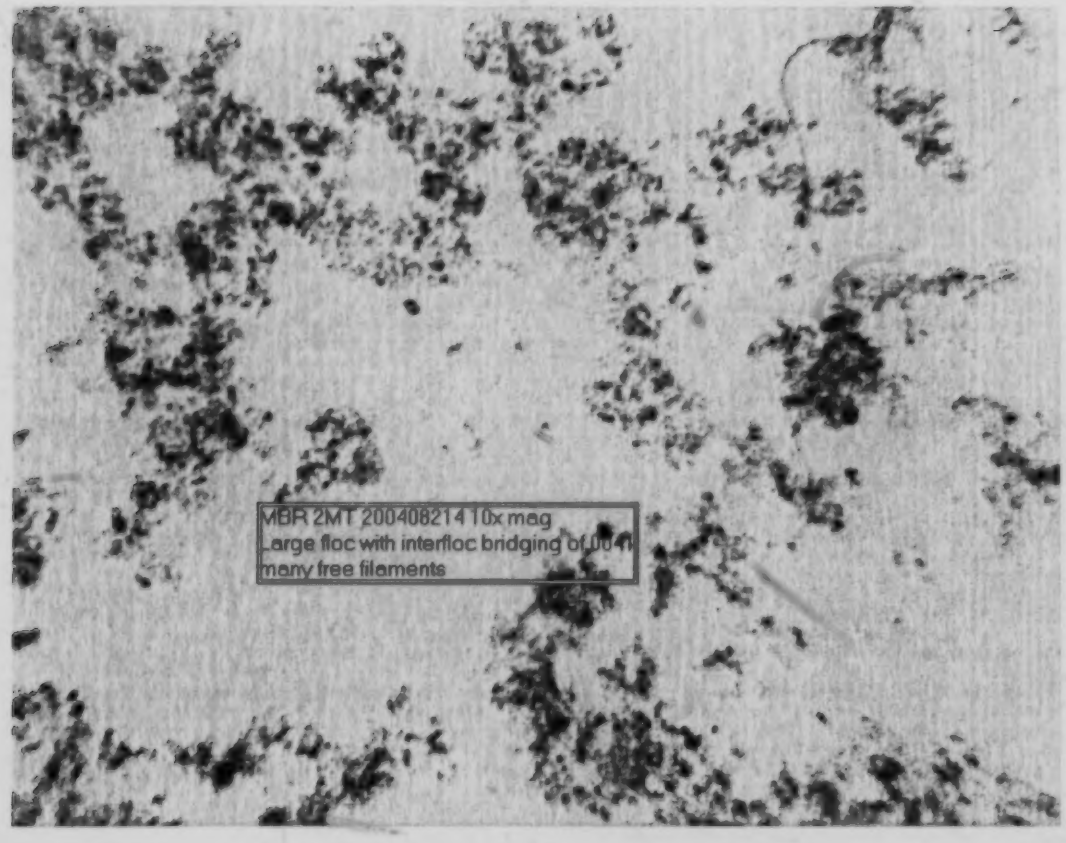

Figure 74. Large floc of 0041 @10×mag for 2MT sludge.[a]

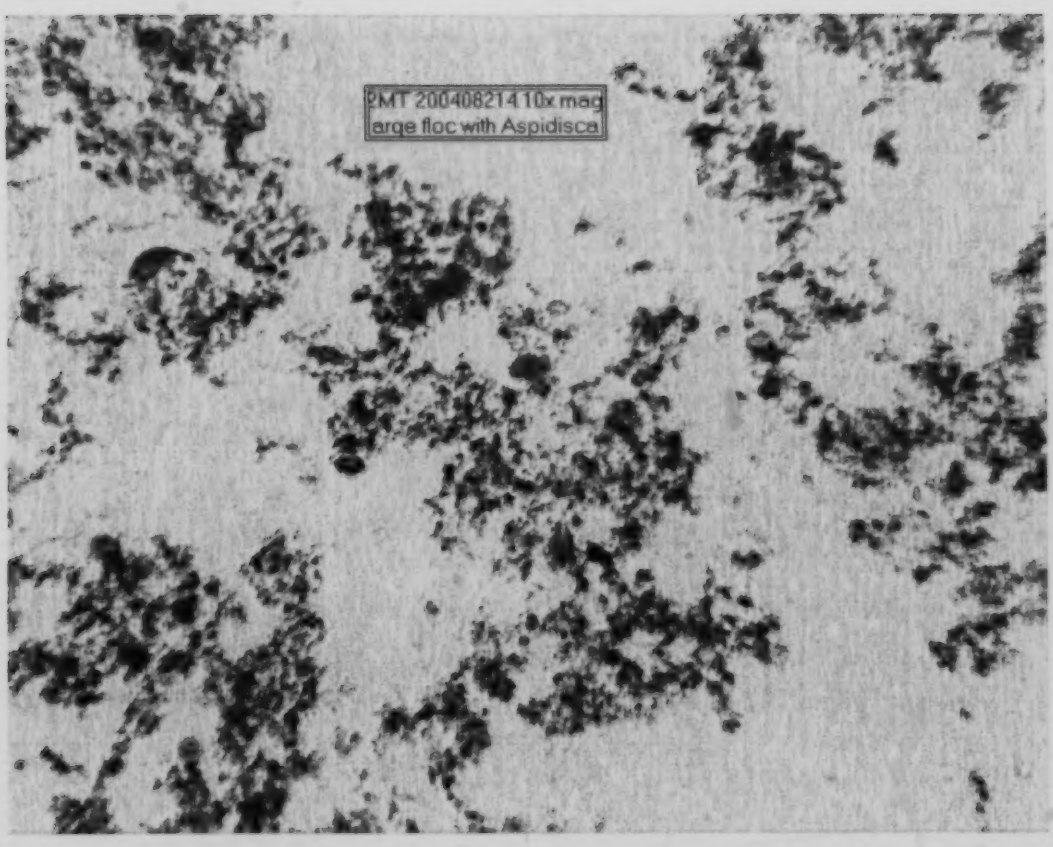

Figure 75. Large floc with Aspidisca @10×mag for 2MT sludge.

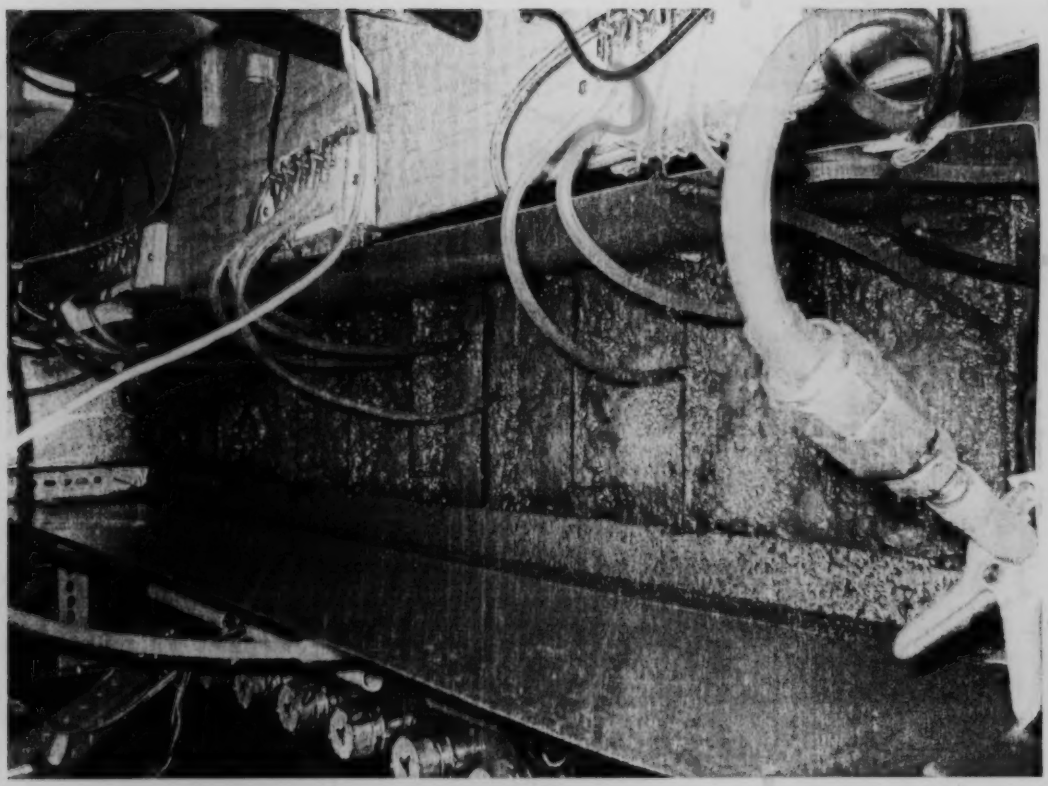

Figure 76. Foam on the surface of the aerobic zone (MBR1, Day 78).

The activated sludge samples on day 93 cannot represent the typical sludge structure for the whole MBR experiment. It should look different from activated sludge of stage I (HRT=6 hours) since no foaming activities were observed during the entire stage I (Figure 77).

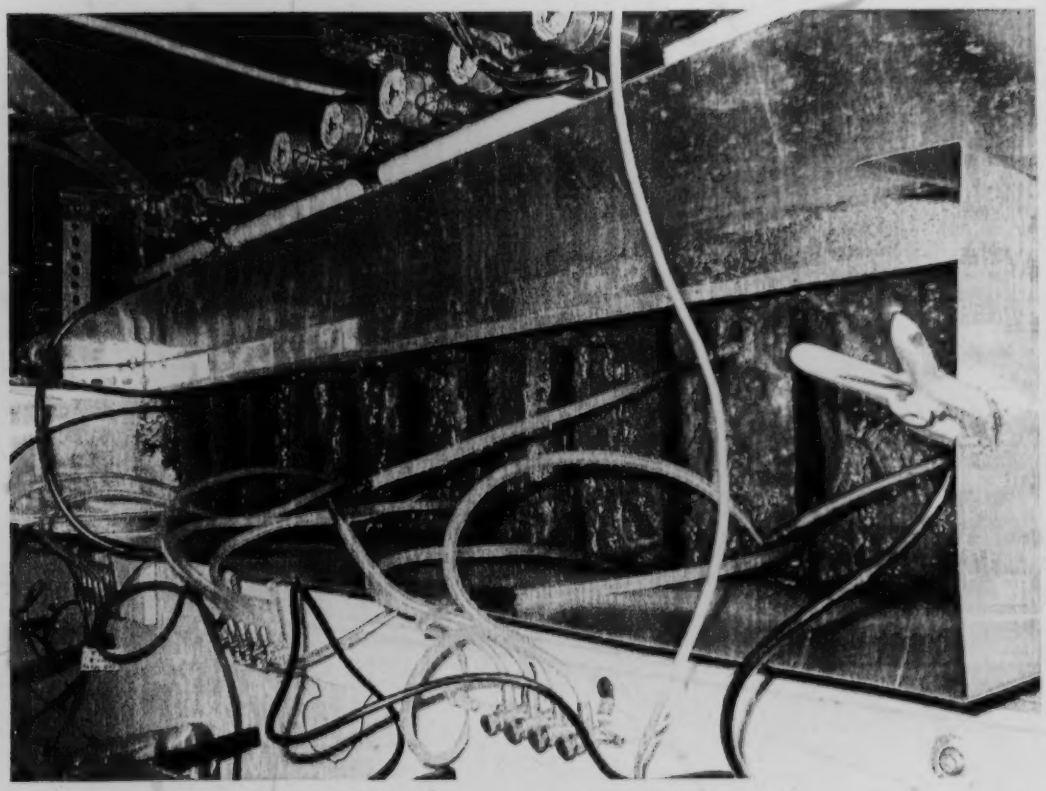

Figure 77. Aerobic zone of MBR2 on day 31, stage I (no foam).

4.3 Permeate Quality

High permeate quality during the entire operation was consistently observed from the startup to the completion of the experiment (day 1 to day 92). Table 32 outlines the permeate quality results of major MBR parameters on the basis of the complete raw data set from day 1 to day 92, without the data processing. The results are presented as the mean, standard deviation, maximum value, minimum value, No. of samples and reduction rate as compared to the MBR-feed. The detailed permeate quality results of each parameter on different stages (6 hours, 8 hours and 4 hours) are presented in later

sections, as compared to GBWWTP final effluent in the same period of time (January 28 to April 29, 2004).

Table 32. Permeate quality results, as compared to the MBR-feed.

Quality Parameter	TSS	BOD_5	COD	TKN	NH_3-N	TOXN	TN	TP	Fecal Coliform	Turbidity
Unit	mg/L	mg/L as O_2	mg/L as O_2	mg/L as N	mg/L as N	mg/L as N	mg/L as N	mg/L as P	CFU/100 mL	NTU
MBR-feed										
Mean	175	270	446	51	32	0.03	51	9.84	2778923	N/A
Stdev.	117	153	115	10	7	0.04	10	4.35	3568846	N/A
Max	690	880	872	91	52	0.22	91	31.10	14000000	N/A
Min	74	130	320	38	19	0.00	38	6.39	66000	N/A
Samples	33	31	36	35	35	37	34	37	13	N/A
MBR1										
Mean	0.78	2	24.06	1.91	0.81	12.55	14.32	1.98	1	0.117
Stdev.	0.44	1	5.73	3.42	3.00	3.29	4.40	1.04	0	0.039
Max	3.00	7.6	40.00	15.96	13.20	20.29	27.73	4.15	1	0.200
Min	0.60	1.6	13.00	0.65	0.01	6.02	7.06	0.30	1	0.084
Samples	33	31	36	36	35	37	34	37	15	31
Reduction rate %	99.4	98.9	94.4	97.0	97.5	N/A	71.5	78.5	100	N/A
MBR2										
Mean	0.74	2	24.05	2.42	1.18	12.90	15.13	1.72	1	0.117
Stdev.	0.28	0	5.07	4.63	3.89	3.60	4.87	1.06	0	0.038
Max	2.00	2	36.00	23.00	18.33	21.90	28.18	4.74	1	0.200
Min	0.60	2	14.50	0.85	0.00	4.39	5.32	0.22	1	0.083
Samples	33	31	36	36	35	37	34	37	15	31
Reduction rate %	99.5	99.0	94.4	96.0	96.3	N/A	70.0	81.3	100	N/A

4.3.1 TSS

Figure 78, 79 and 80 illustrate the solids reduction performance of MBRs as compared to GBWWTP-BNR. The TSS comparison was made based on the sampling period from day

1 to day 92. TSS concentrations averaged 175 mg/L for MBR-PE-feed as compared to 122 mg/L for GBWWTP-PE-feed and 0.78 mg/L for MBR1 permeate, 0.74 mg/L for MBR2 permeate, as compared to 6.68 mg/L for GBWWTP final effluent. TSS reduction rates averaged 99.43% for MBR1 and 99.46% for MBR2, as compared to 94.25% for GBWWTP final effluent. TSS results indicated that MBR systems outperformed GBWWTP conventional system regardless of the variations in solids loading to the systems. Solid reduction in MBRs is solely dependent on the pore size and the integrity of the membrane.

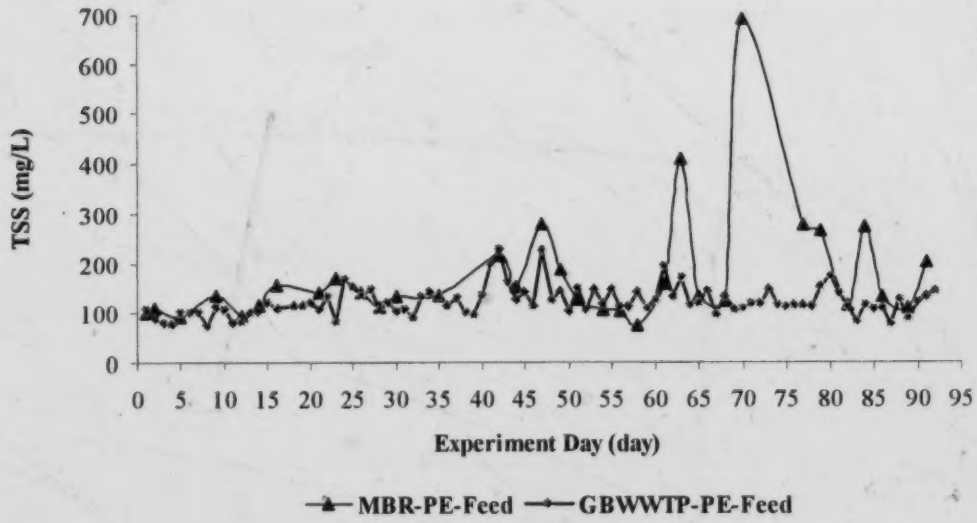

Figure 78. TSS concentrations of MBR-PE and GBWWTP-PE.

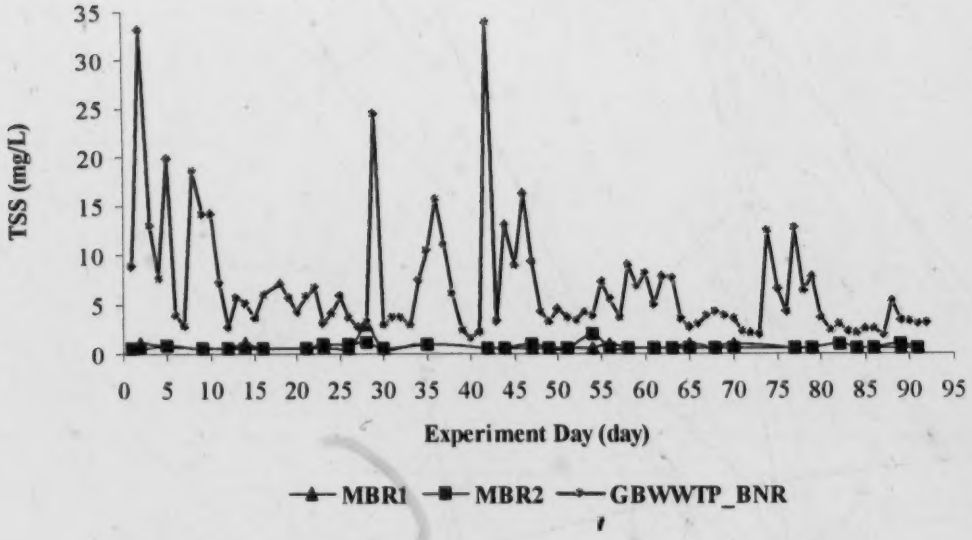

Figure 79. TSS of MBR permeates as compared to GBWWTP final effluent.

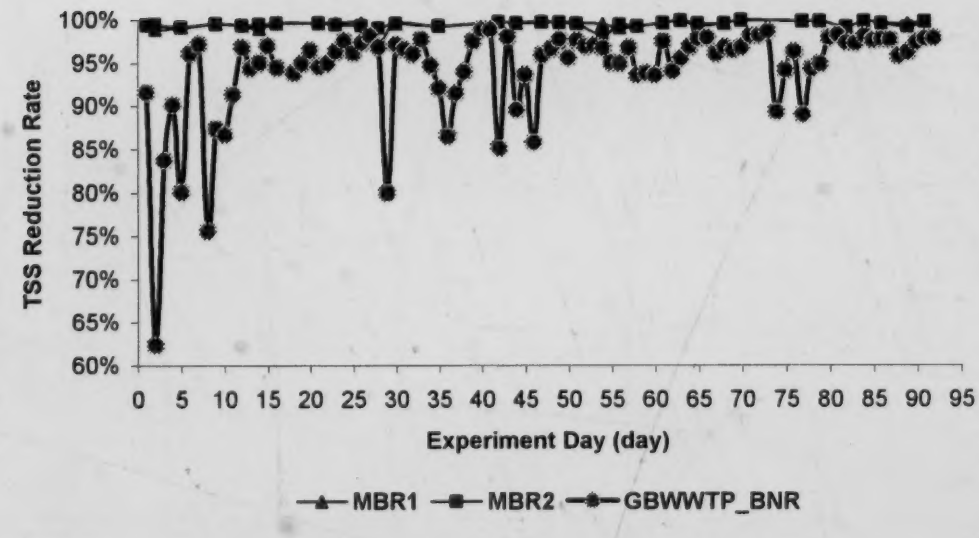

Figure 80. TSS reduction comparison between MBRs and GBWWTP.

4.3.2 Turbidity

Figure 81 shows the turbidity of MBR permeates as compared to deionized (DI) water. Turbidity averaged 0.117 NTU for both MBRs and 0.056 NTU for DI water. It was observed that turbidity measurements for MBR permeates were largely influenced by fine air bubbles in permeates due to the suction pressure. Permeate turbidity varied on the time intervals between the turbidity tests and the samplings, especially when the permeate values are at the very low range (below 0.2 NTU). Higher suction pressure caused more dissolved air in permeates and ultimately increased the permeate apparent turbidity. The permeate turbidity tested in the afternoon was always lower than the turbidity tested in the morning right after the sample was taken. Since this issue was noticed, the turbidity results obtained after day 30 were more stable as they were tested in afternoons when the permeate samples were shaken and placed quietly for a few hours. Figure 82 shows the visual qualities of the MBR permeate on site.

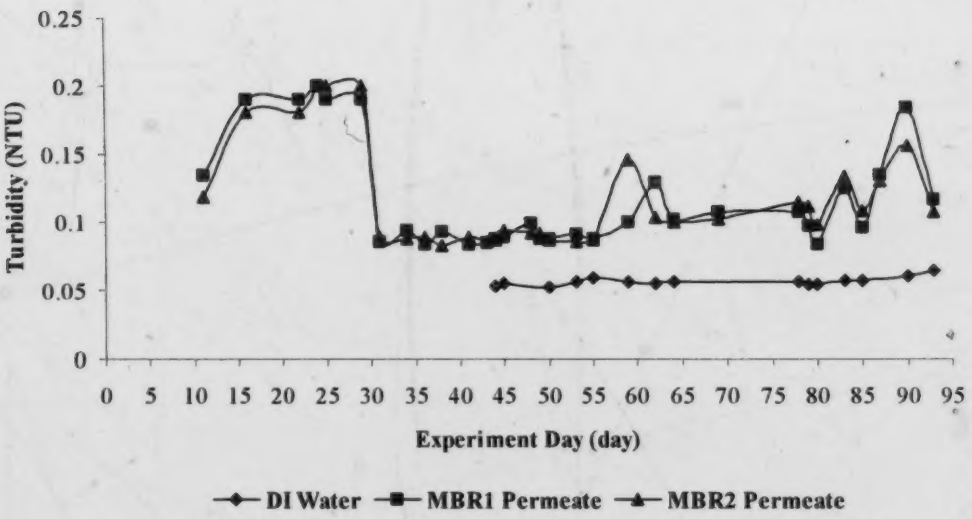

Figure 81. The turbidity of MBR permeates V.S. deionized water.

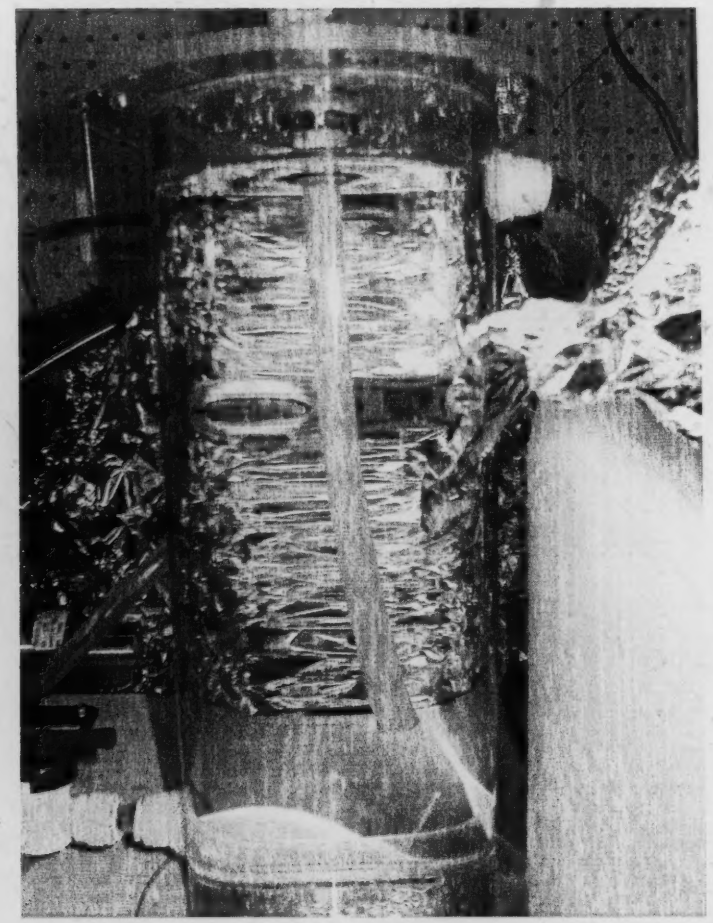

Figure 82. MBR2 permeate in the backpulse container on day 40.

4.3.3 Particle Count

Particle count results indicated high permeate visual quality and high MBR performance. Table 33 shows the average particle count results of MBRs as compared to DI water. The particle count measurement started on day 15. The results were obtained from day 15 to day 92. During the particle count tests, a DI water sample was also measured for particle count prior to permeate measurements. Figure 83 illustrates the particle count results of MBR permeate with a reference of DI water samples. Similar to turbidity, particle count

results were also influenced by the dissolved air in permeates and even more sensitive to the change of suction pressure. It was observed that in the later period of the experiment particle counts increased and fluctuated due to the high suction pressure. The dissolved air influence was visually proved by shaking permeate samples and DI water samples. When the sample bottles were shaken, a lot more fine air bubbles rose up in the permeate sample while much less fine air bubbles appeared in the DI water sample. Other tests performed for the dissolve air influence included particle count tests on different days for the same permeate sample. The particle count result of a permeate sample tested on the collection day was always higher than that of the same sample tested on the other day. Figure 84 shows the particle count comparison of the same permeate samples tested on different days.

Table 33. Particle count results of MBRs

Samples	DI Water	DI Water	1P	1P	2P	2P
Unit	2μm	5μm	2μm	5μm	2μm	5μm
Mean	9	3	19	7	19	7
STDEV	3	1	14	5	10	5
Max	13	5	76	20	43	20
Min	3	1	5	1	7	2
No. of Samples	20	20	28	28	28	28

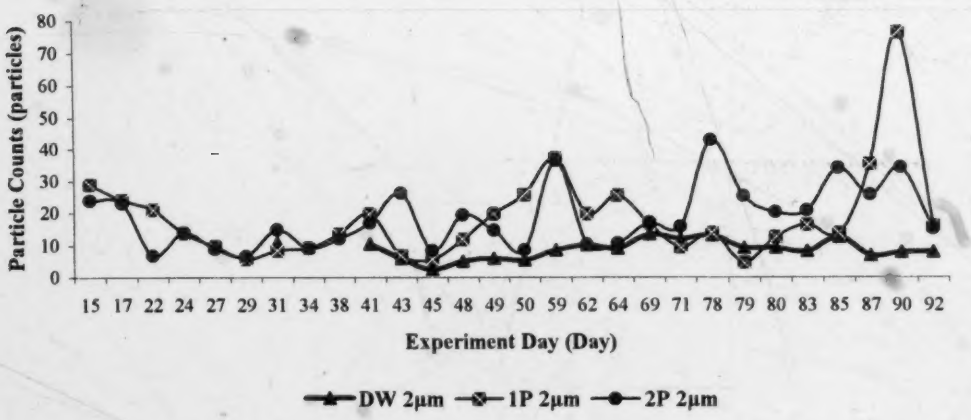

Figure 83. The particle count results of MBR permeates, as compared to DI water.

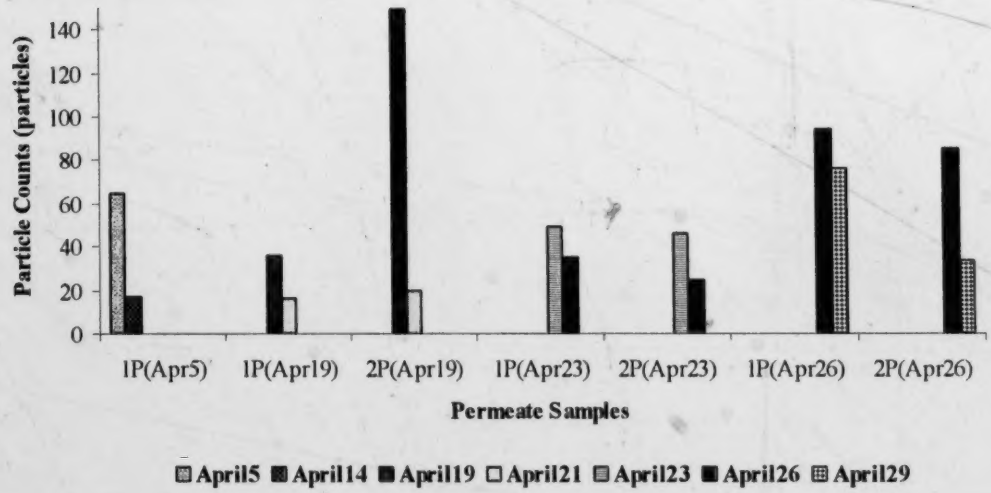

Figure 84. The particle (2μm) count comparison of the same permeate samples tested on different days.

4.3.4 Microorganism Reduction

GBWWTP laboratory performed coliform tests on weekly basis. Table 34 presents the detailed results of total coliform (CO-T-M) and fecal coliform (CO-F-M) for MBR feed

and permeates. The coliform results show the high performance of MBRs for the microorganism reduction. Fecal coliform results in permeates were consistently under the detection limit of 1 CFU/100 mL over the entire study period. Total coliform results during the startup were slightly higher in both MBRs prior to day 16. Then total coliform in MBR1 permeate was also consistently under the detection limit until the completion of the experiment. Total colifom in MBR2 permeate ranged 1 to 7 CFU/100 mL after day 36.

Although the nominal pore size of membrane is 0.04 μm, some pore size may still be larger than 0.04 μm due to a normal distribution of pore sizes. These larger pore sizes may allow some small coliform (0.3 to 0.6 μm) to pass through the membrane in the beginning of the experiment. When the biofilm was built up on membrane surface, it might served as a filtration barrier to prevent more small bacteria from passing through the membrane. The total coliform then reduced after the buildup of a biofilm layer. It should not be any concerns about the integrity of both ZW-10 membrane modules. The typical lumen diameter of hollow fibre is 500 to 2000 μm. Any cuts or holes on a single fibre may cause a significant microorganism breakthrough. The total coliform resuts from MBR2 permeate also indicated that ZW-10 membrane module (W102046) used in MBR1 may have a better quality than the membrane module (W102047) in MBR2. It was also confirmed by the membrane integrity test discussed in section 3.3.1. The pressure decay of W102047 (0.83 kPa/min) was slightly higher than W102046 (0.34 kPa /min).

Table 34. Total and fecal coliform for MBR feed and permeates (CFU/100 mL).

Experiment	MBR-feed		MBR1		MBR2	
Day	CO-T-M	CO-F-M	CO-T-M	CO-F-M	CO-T-M	CO-F-M
1	-	-	1	1	1	1
5	tntc	tntc	44	1	48	1
9	38000000	2200000	25	1	90	1
14	27000000	3500000	12	1	8	1
16	22000000	3900000	6	1	4	1
21	47000000	190000	1	1	8	1
28	31000000	1900000	1	1	3	1
36	2500000	2500000	1	1	28	1
43	10800000	1000000	1	1	5	1
50	15300000	1200000	1	1	1	1
64	30000000	970000	1	1	4	1
70	14000000	14000000	1	1	1	1
77	20000000	66000	1	1	7	1
84	20000000	2900000	1	1	1	1
91	9100000	1800000	1	1	2	1
Mean	22053846	2778923	7	1	14	1
STDEV	12382623	3568846	12	0	25	0
Max	47000000	14000000	44	1	90	1
Min	2500000	66000	1	1	1	1
Samples	13	13	15	15	15	15

The previous MBR study (Heise, 2002) indicated that once microorganisms pass through into the membrane lumen, the microorganisms may probably grow within membrane element or permeate withdrawal system, and the microorganism contamination will be very difficult to remove. In this study, the results of high performance of microorganism reduction in both MBRs presents a contradiction to the conclusion obtained from the previous MBR study. Total coliform in MBR permeates were reduced to detection level

limit without any cleanings after the presence in the initial stage of the experiment. One would explain that as long as the membrane keeps integrity, a small amount of microorganism passing through membrane will be hard to survive and will be probably washed out of the system. However, large contamination in the backpulse tank may be more difficult to control.

4.3.5 BOD_5 Reduction

The 5-day biochemical oxygen demand (BOD_5) tests for MBR feed and permeates were started from day 12, three times a week by GBWWTP laboratory. Over the entire study period, BOD_5 in both MBR permeate was consistently reduced to below detection level limit (2 mg O_2/L) regardless of hydraulic loadings, except for three occasional cases where BOD_5 in MBR1 permeate was slightly higher than the detection level limit. Figures 85 and 86 illustrate the BOD_5 results averaged 2 mg O_2/L, over 99% reduction rates in both MBRs as compared with an average 4.74 mg O_2/L, 97% reduction rate of BOD_5 for GBWWTP BNR system. High BOD_5 reduction indicated a high performance on the removal of biodegradable organics in BNR-MBR systems, which may be attributed to high efficiency of biological removal in the bioreactor as well as ultrafiltration by membrane.

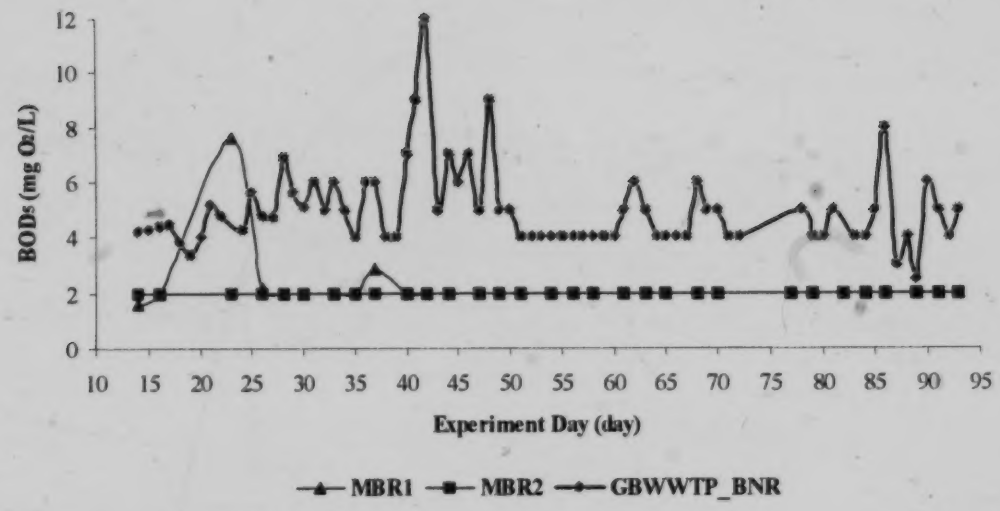

Figure 85. BOD_5 (all MBR1 and MBR2 values < 2 mg/L except for 3 occasions for MBR1) of MBR permeates, as compared to GBWWTP final effluent.

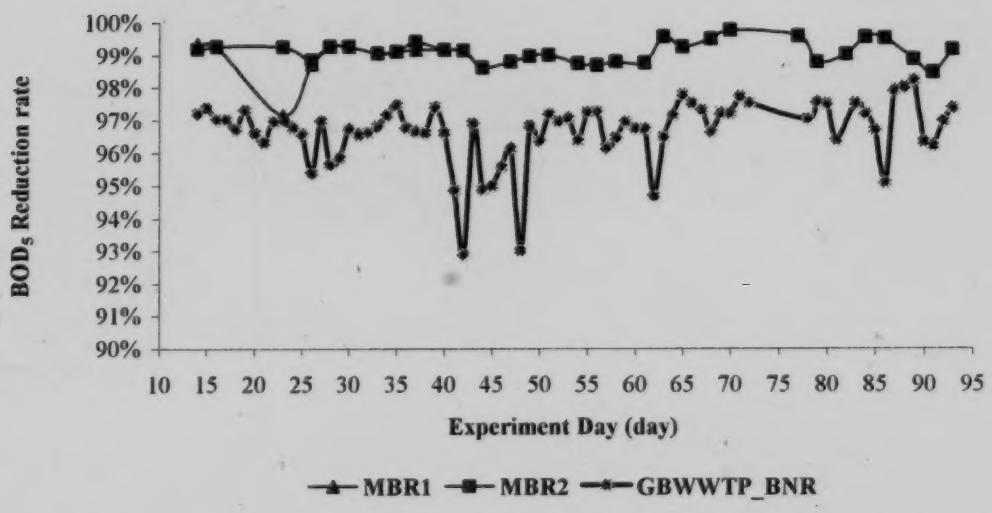

Figure 86. BOD_5 reduction rates of MBR permeates, as compared to GBWWTP BNR final effluent.

It was observed that BOD_5 in MBR-PE-feed was mostly higher than GBWWTP PE feed (Figure 87) although they were all coming from GBWWTP primary effluent. This can be explained that during operation the mixed liquor backflow to feed tanks sometimes happened when the water level was adjusted or the R3 pump tubing was changed. The mixed liquor backflow increased the organics and biomass content in MBR feed tank. This unavoidably resulted in higher BOD_5 and COD in MBR PE feed than GBWWTP PE feed (Figures 88 and 89). The ratio of BOD_5 over COD in MBR PE feed averaged 59% and fluctuated more during the late operation period (after day 65).

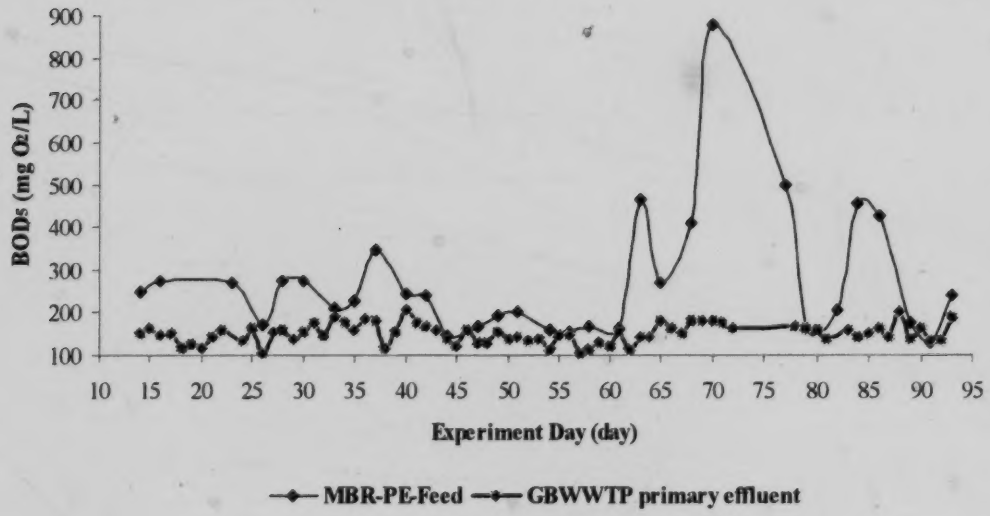

Figure 87. BOD_5 in both MBR-PE-Feed and GBWWTP primary effluent.

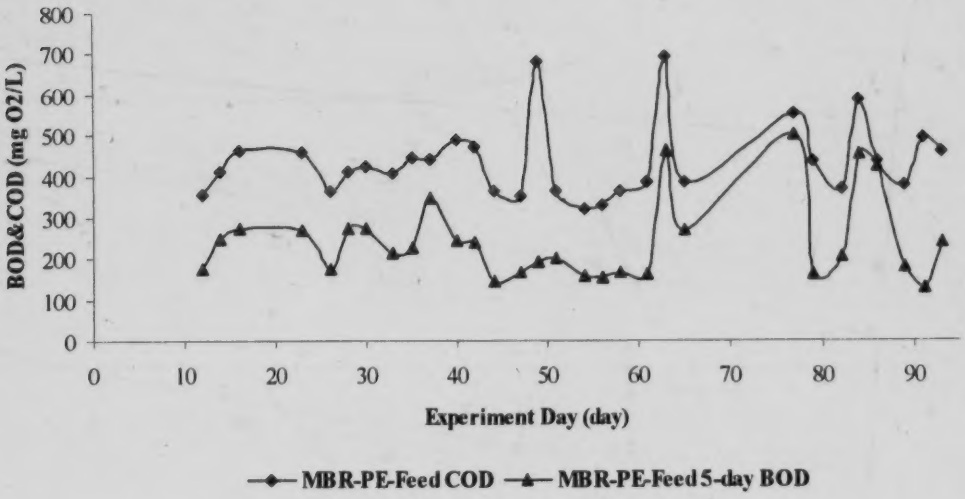

Figure 88. BOD_5 V.S. COD in MBR PE feed.

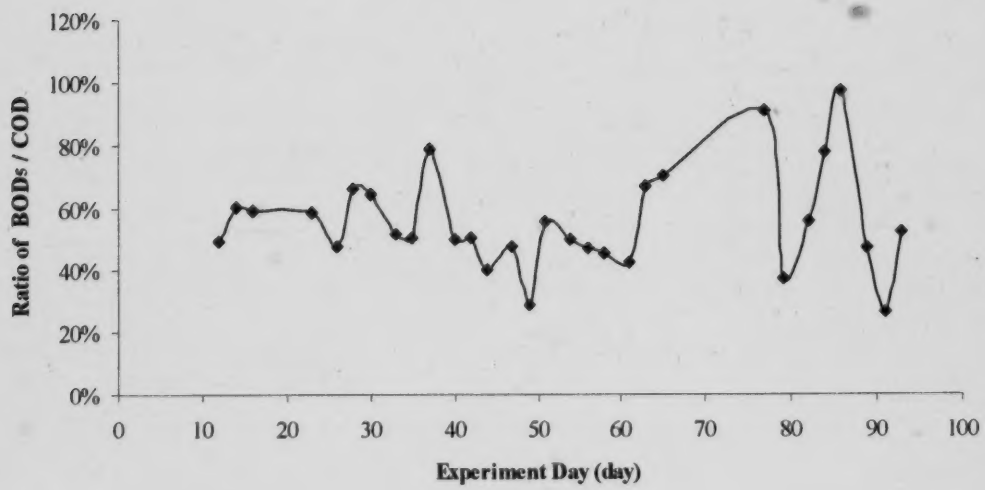

Figure 89. The ratio of BOD_5 over COD in MBR-PE-Feed.

4.3.6 COD Reduction

High performance of COD reduction was consistently observed for the BNR-MBR systems over the 93-day operation period. With an average COD of 446 mg/L in MBR-feed, a 94.4% COD reduction efficiency was achieved by both MBRs, averaged 24 mg/L COD concentration in both permeates. In the same period, GBWWTP full scale BNR system achieved a 86.4% COD reduction rate, averaged 41 mg/L COD in final effluent with an average COD of 312 mg/L in primary effluent feed.

Figures 90, 91 and 92 illustrate COD reductions for both MBRs and GBWWTP. Similar to BOD, COD in MBR-PE-Feed was also higher than COD in GBWWTP-PE-Feed, especially in the later period of the experiment. It further confirmed that MBR-PE-Feed may contain some mixed liquor resulted from the mixed liquor backflow. The mixed liquor content increased COD in MBR-PE-Feed and also reduced the ratio of soluble COD (Figure 93). In MBR-PE-Feed, the soluble COD averaged 159 mg/L with an average low soluble COD ratio of 37.4%

The consistent high COD reduction regardless of hydraulic loading indicated that not only a good biodegradable COD reduction was achieved in MBR bioreactors, but also a high efficiency of non-biodegradable COD reduction was obtained through the membrane filtration. Most non-biodegradable substances were ultimately removed through sludge wasting. Only small fraction of non-biodegradable substances (less than 0.04 μm) passed through the membrane.

The permeate COD consists mainly of aquatic humic substances, which are naturally occurring compounds. They are hard to biodegrade aerobically and are responsible for the yellowish hue of treated wastewater effluent. These substances may include humin, humic and fulvic acids (Heise, 2002).

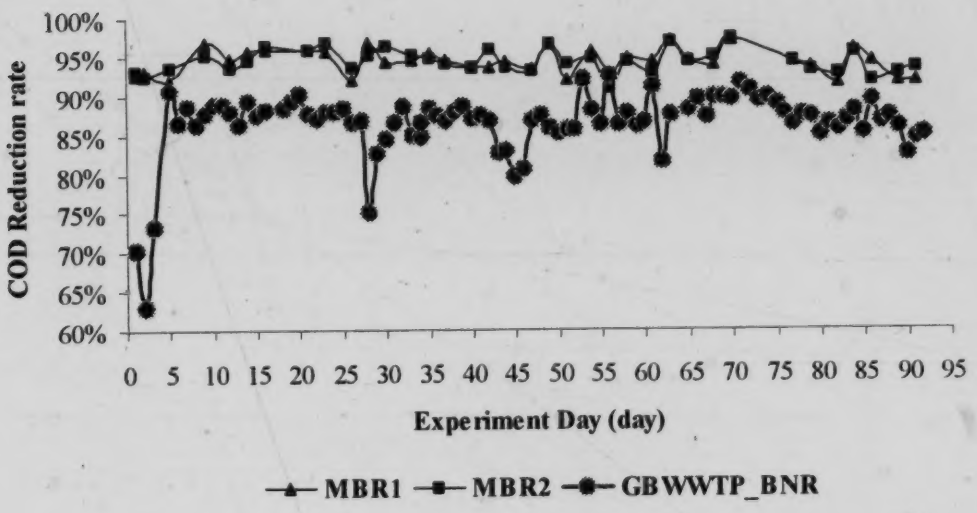

Figure 90. COD reduction rates of MBR permeates, as compared to GBWWTP final effluent.

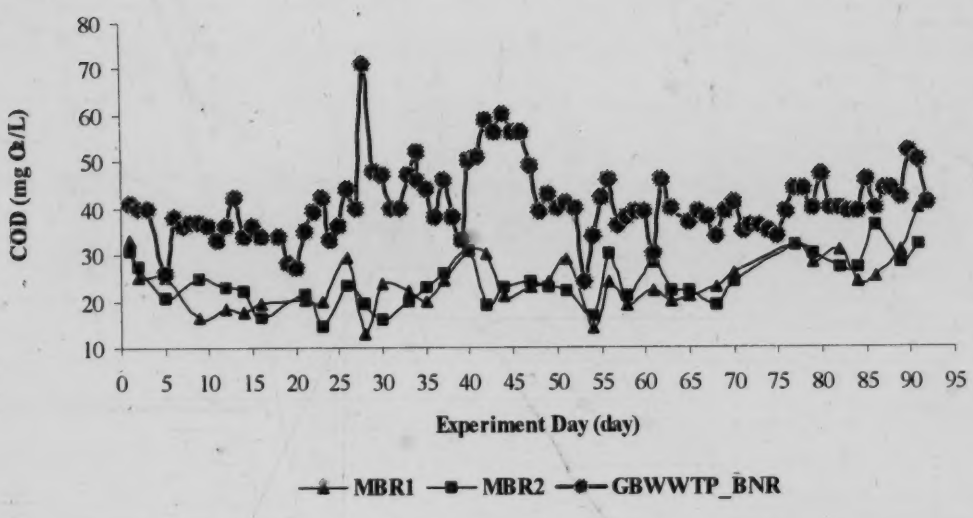

Figure 91. COD concentrations in MBR permeates, as compared to GBWWTP final effluent.

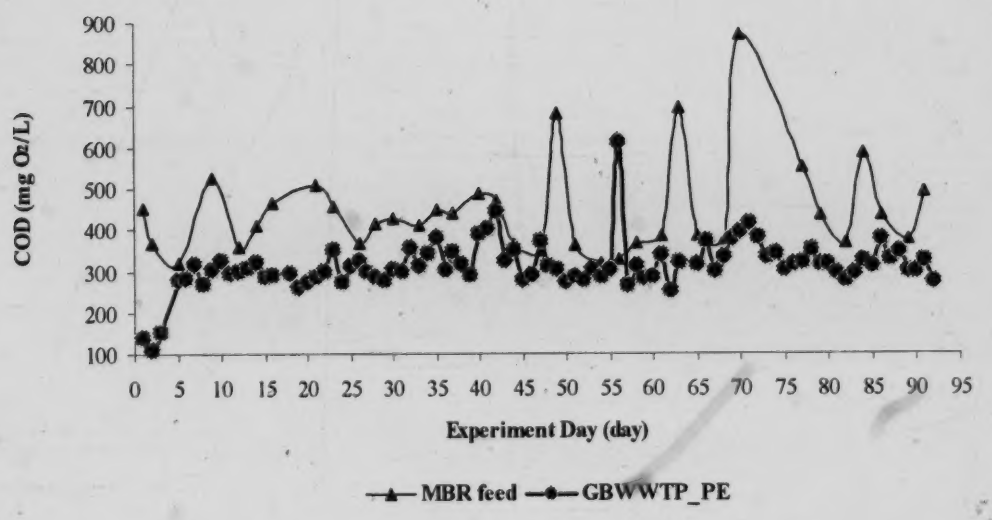

Figure 92. COD concentrations in MBR-PE-Feed, as compared to GBWWTP primary effluent.

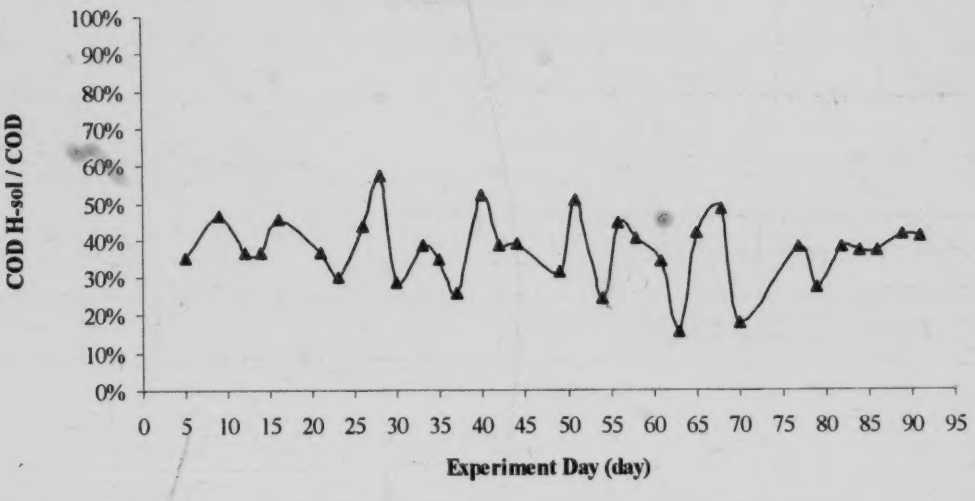

Figure 93. Soluble COD ratio in MBR-PE-Feed.

4.3.7 NH_3-N and TKN Reduction

High reduction rates of ammonia nitrogen (NH_3-N) and TKN nitrogen (organic N + NH_3-N) were consistently achieved regardless of hydraulic loadings after the startup (day 12). Over three different HRT stages (6 hours, 8 hours and 4 hours), the average NH_3-N reduction rates for MBR1 and MBR2 were 99.87% and 99.76% with the very low standard deviations of 0.22% and 0.55%, respectively. In the same period, GBWWTP full-scale BNR system only reached an average NH_3-N reduction rate of 64.2% with very high standard deviation of 14.5%. Similarly, the average TKN reduction rates reached 98.2% for MBR1 and 98.2% for MBR2 also with the very low standard deviation of 0.7% for both MBRs, as compared to GBWWTP, averaged 71.5% of TKN reduction rate (Figures 94 and 95).

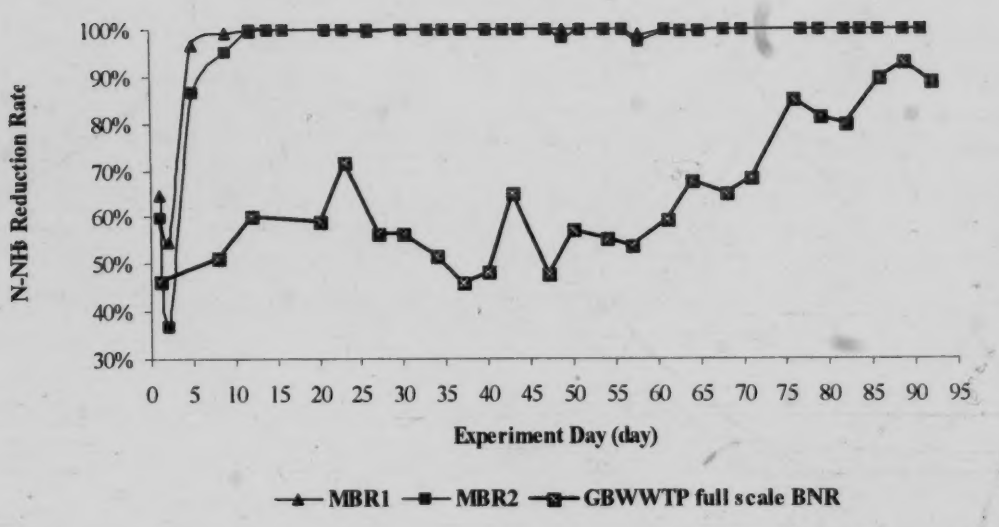

Figure 94. NH_3-N reduction rates of MBRs, as compared to GBWWTP full-scale BNR system.

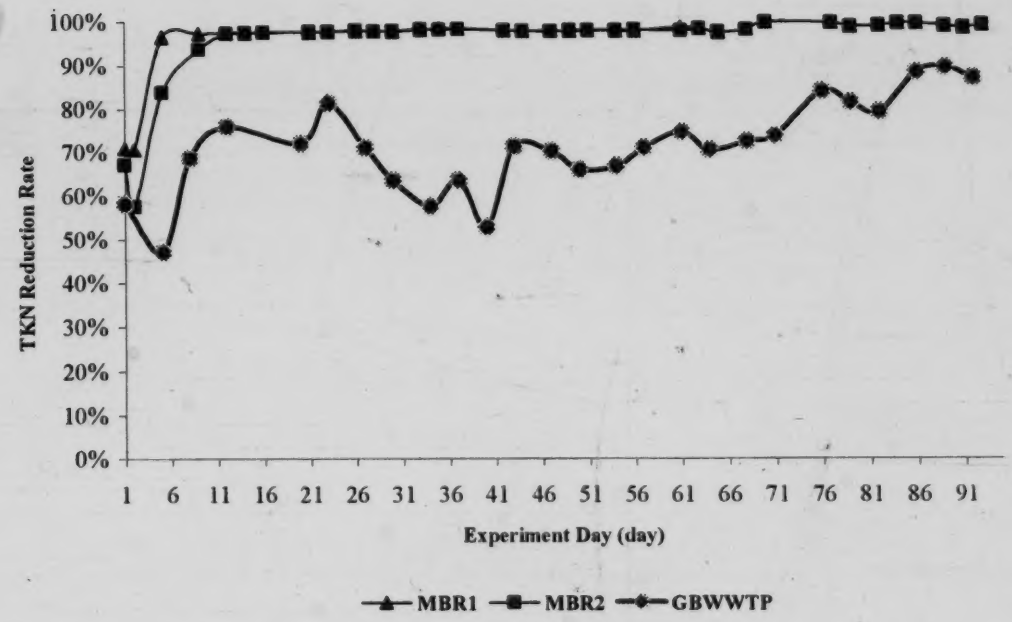

Figure 95. TKN reduction rate in MBRs, as compared to GBWWTP full-scale BNR system.

For an average 32.3 mg/L of NH_3-N concentration in the MBR-Feed, both MBRs almost achieved complete NH_3-N removal with average permeate NH_3-N concentrations of 0.04 mg/L for MBR1 and 0.08 mg/L for MBR2 over all three HRT stages, as compared to GBWWTP with an average 8.15 mg/L of NH_3-N in combined final effluent (Figure 96). Due to high performance of NH_3-N reduction and organic nitrogen reduction, TKN level remained consistently low, averaged 1.05 mg/L of TKN for both MBR1 and MBR2 with very low standard deviations of 0.12 and 0.09 mg/L, respectively. In the meantime, GBWWTP kept high TKN in its combined final effluent, which averaged 11.67 mg/L with high standard deviation of 5.13 mg/L (Figure 97).

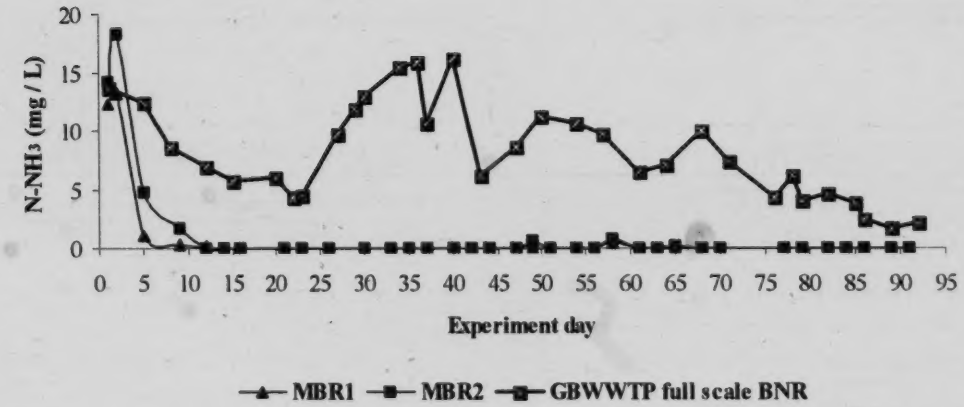

Figure 96. NH_3-N concentrations in MBR permeates, as compared to GBWWTP final effluent over the entire study period.

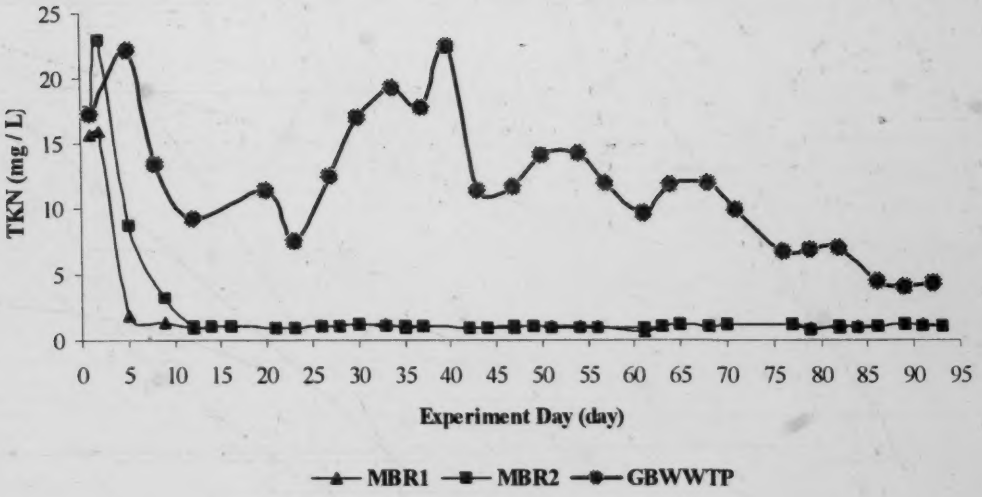

Figure 97. TKN concentrations in MBR permeates, as compared to GBWWTP final effluent over the entire study period.

Both NH_3-N and TKN in MBR-PE-Feed kept higher levels than that of GBWWTP-PE-Feed. NH_3-N in MBR-PE-Feed averaged 32.3 mg/L, 47% higher than an average 22.0 mg/L of NH_3-N in GBWWTP-PE-Feed (Figure 98). Similarly, TKN in MBR-PE-Feed averaged 51.0 mg/L, as compared to an average 40.8 mg/L of TKN in GBWWTP-PE-Feed (Figure 99). It confirmed again that the occasional mixed liquor backflow may be the main cause for the high concentrations of NH_3-N and TKN in MBR tanks.

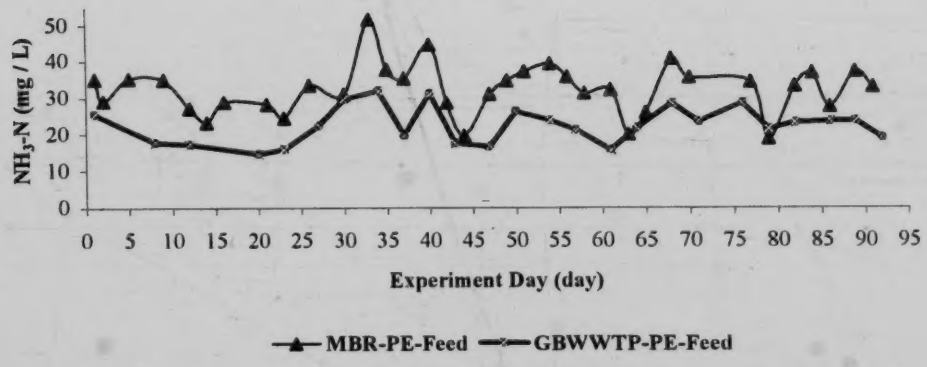

Figure 98. NH_3-N concentrations in MBR-PE-Feed, as compared to that of GBWWTP-PE-Feed.

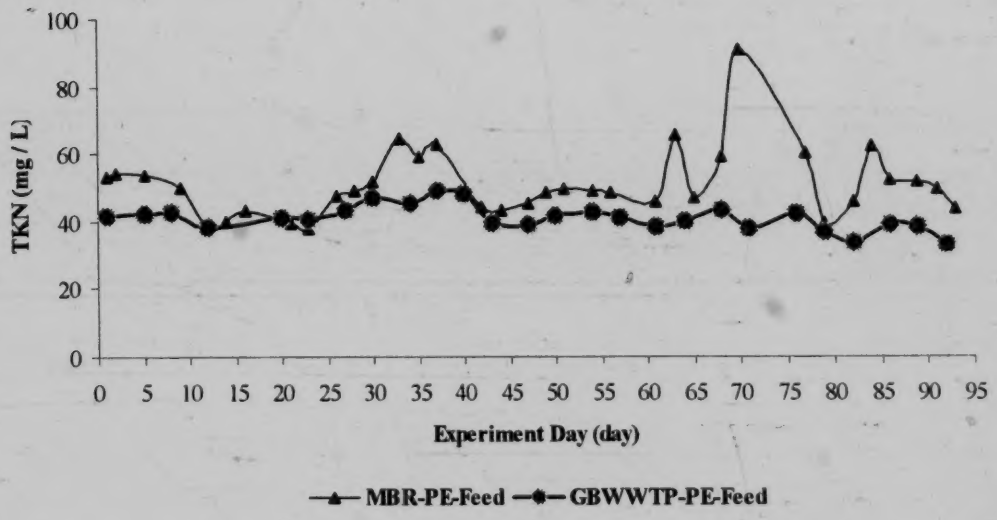

Figure 99. TKN concentrations in MBR-PE-Feed, as compared to that of GBWWTP-PE-Feed.

TKN nitrogen included ammonia nitrogen and organic nitrogen. Ammonia nitrogen is reported to account for about 60 to 70 percent of the influent TKN. In MBR systems,

NH_3-N accounted for approximately 63.0% of the MBR-PE-Feed TKN nitrogen, which was higher than an average 53.9% of TKN nitrogen in GBWWTP-PE-Feed. It was interested to observe that the ratio of ammonia nitrogen over TKN for MBR-PE-Feed sharply reduced from 63.0% to 2.8% in MBR1 permeate, 2.9% in MBR2 permeate. On the contrary, the ratio of NH_3-N / TKN for GBWWTP-PE-Feed increased from 53.9% to 66.8% in GBWWTP combined final effluent (Figures 100 and 101). The comparison of the ratios of NH_3-N over TKN between MBR pilot plants and GBWWTP full-scale BNR system clearly indicated the high efficiency of NH_3-N reduction in MBRs, as compared to the poor performance of NH_3-N reduction at GBWWTP. This can be explained that high MLSS concentrations obtained from long SRT operation helped the BNR-MBR systems to maintain a high fraction of nitrifying organisms and to enhance the oxidation of ammonia. The MBR results of ammonia nitrogen reduction may provide a good technical solution for GBWWTP to have a better control of ammonia reduction.

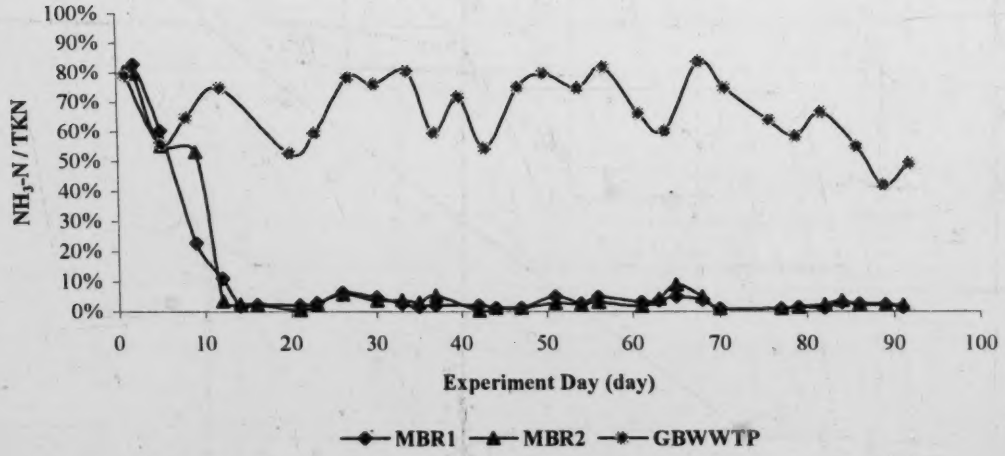

Figure 100. The ratio of NH_3-N over TKN for MBR permeates, as compared to GBWWTP final effluent.

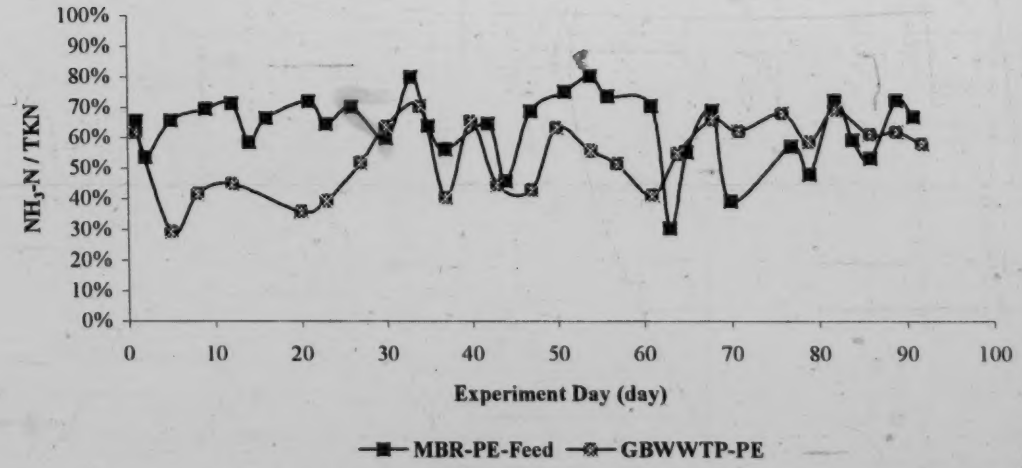

Figure 101. The ratio of NH_3-N over TKN for MBR-PE-Feed, as compared to GBWWTP-PE.

4.3.8 TOXN and TN Reduction

Due to the high efficiency of ammonia oxidation in BNR-MBR pilot plants, the total oxidized nitrogen (TOXN=NO_3^- + NO_2^-) remained also high in MBR permeates, averaged 12.55 mg/L, 12.90 mg/L for MBR1 and MBR2, respectively, over the entire study period. The GBWWTP had a lower average 9.5 mg/L of TOXN level in combined final effluent (Figure 102). For HRT stage I (from day 14 to day 45), MBR1 and MBR2 both had a slight better performance, where permeate TOXN concentrations were 9.12 mg/L and 10.05 mg/L, respectively (Figure 103). It was probably because that the MBR operation was most stable during HRT stage I in terms of hydraulic loading and recirculations.

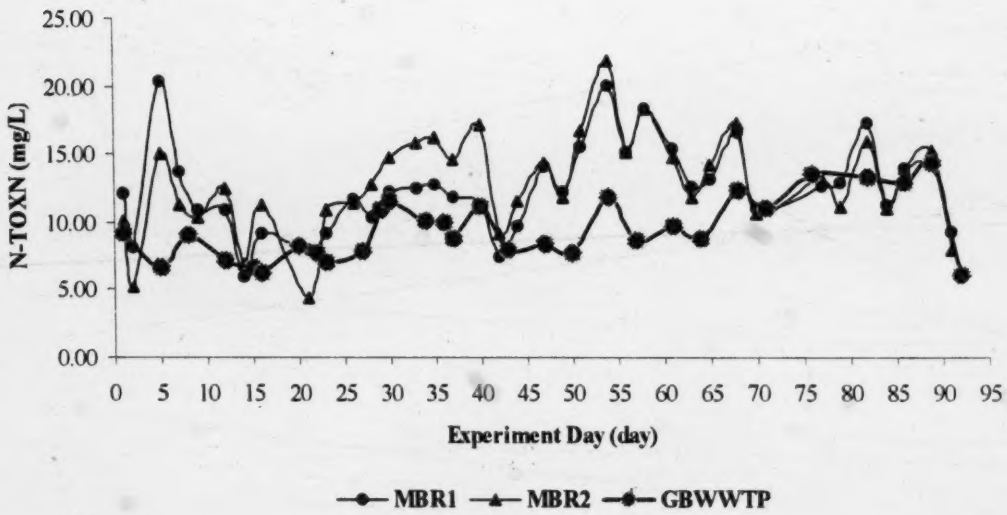

Figure 102. TOXN in MBR permeates, as compared to GBWWTP final effluent over the 92 day study period.

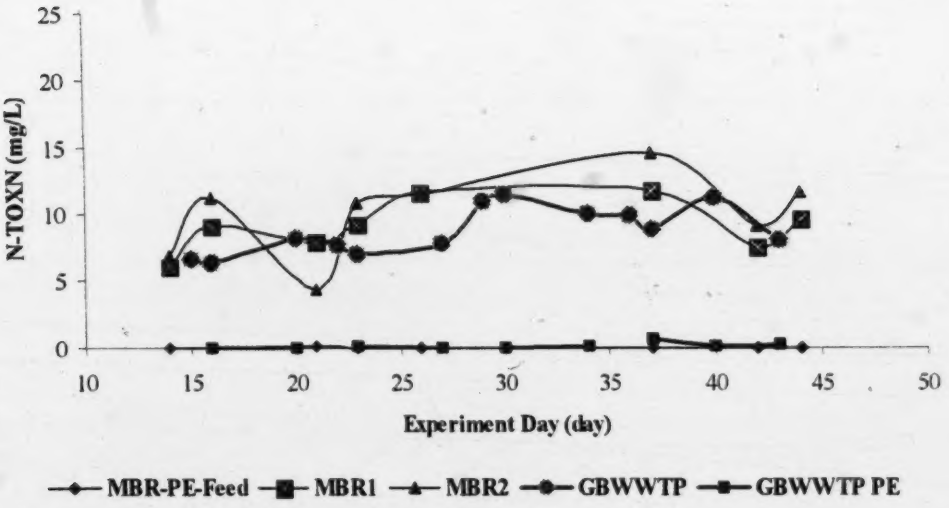

Figure 103. TOXN concentrations both MBR feed and permeates, as compared to GBWWTP final effluent and primary effluent over stage I (Day 14 to day 45).

Several measures were taken during the operation to try to increase the denitrification. These measures included relocation the mixed liquor recycle lines, adjustment of the recycle rates, reduction of the aeration for last cells of the aeration zones and added recirculation containers. No significant improvements were observed for denitrification. This may be explained that the excess dissolved oxygen in the returned nitrified mixed liquor to anoxic zones out competed nitrate or nitrite as an electron acceptor for the oxidation of a variety of organic or inorganic electron donors. Therefore the denitrification efficiency was decreased.

Although TOXN in MBR permeates was slightly higher than that of GBWWTP during the study period, it did not necessarily mean that GBWWTP had a better denitrification than MBRs. On the contrary, both MBRs had much better denitrification even though its

TOXN level was relatively higher than that of GBWWTP. The reason was that the TOXN converted from the oxidation of ammonia nitrogen in MBRs was initially much higher than that of GBWWTP due to the high efficiency of ammonia reduction in MBRs and the poor nitrification performance of GBWWTP. Without considering the assimilation of NH_3-N by microorganisms and the production of NH_3-N by endogenous respiration in the bioreactor, the denitrification rate could be approximately estimated by comparing the total amount of TOXN and NH_3-N presented in the PE feed to that existed in the permeates or final effluent. Over the entire study period, denitrification in MBRs was achieved by average 57.6% for MBR1 and 55.5% for MBR2, as compared to an low average 19.6% of denitrification rate in GBWWTP (Figure 104). This can be explained that during January to April, GBWWTP was operating at a "Winter BNR Mode", by which the anoxic zone was changed to aerobic zone by providing the aeration. This mode was designed to increase aeration zone and enhance the nitrification at cost of sacrificing the denitrification.

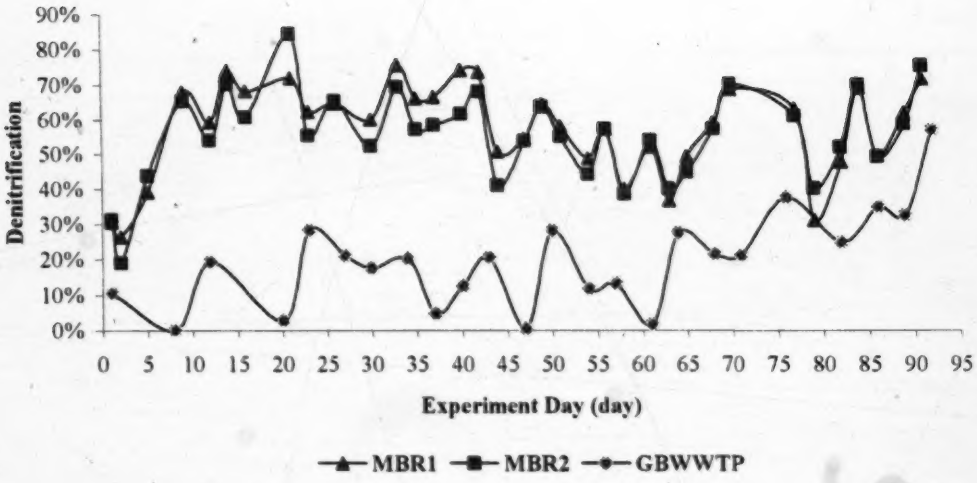

Figure 104. Denitrification of MBRs V.S. GBWWTP over the 92 day study period.

Total nitrogen (TN) consists of the total oxidized nitrogen (TOXN) and TKN. Over the 92 day study period, the average TN reduction rates achieved by MBR1 and MBR2 were 73.7%, 72.7%, respectively. It was about 25% higher than the TN reduction rate of GBWWTP, averaged 47.5% over the same period (Figure 105)

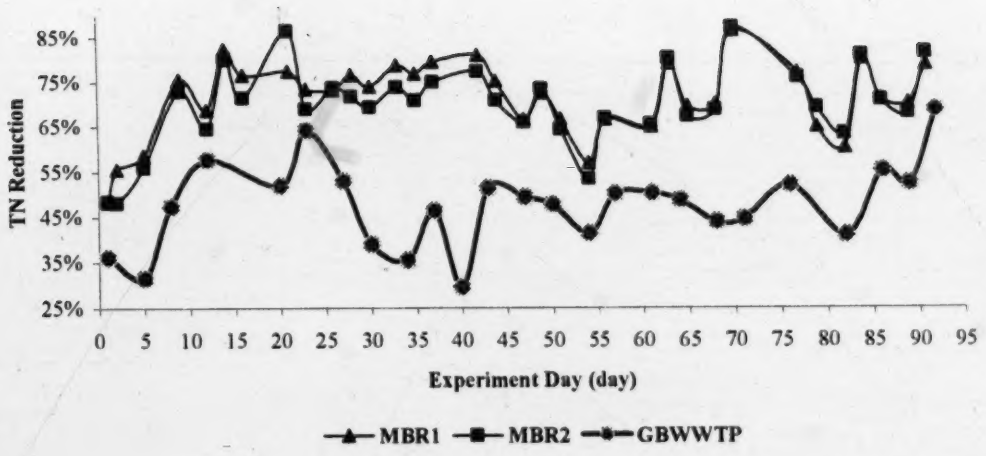

Figure 105. TN reduction rates of MBRs, as compared to GBWWTP over the 92 day study period.

4.3.9 TP Reduction

Over the 92 day study period, the average total phosphorus (TP) reduction rates were 78.5% for MBR1 and 81.3% for MBR2. The average total phosphorus concentrations for MBR1 and MBR2 permeate were 1.98 mg/L and 1.72 mg/L, respectively. The data included all sampling days from the startup to the completion of the experiment. In the same period, GBWWTP full-scale BNR system achieved a relative higher total phosphorus reduction than MBRs. The average TP reduction of GBWWTP was 89.4%, with an average TP concentration of 0.8 mg/L in GBWWTP combined final effluent (Figures 106 and 107).

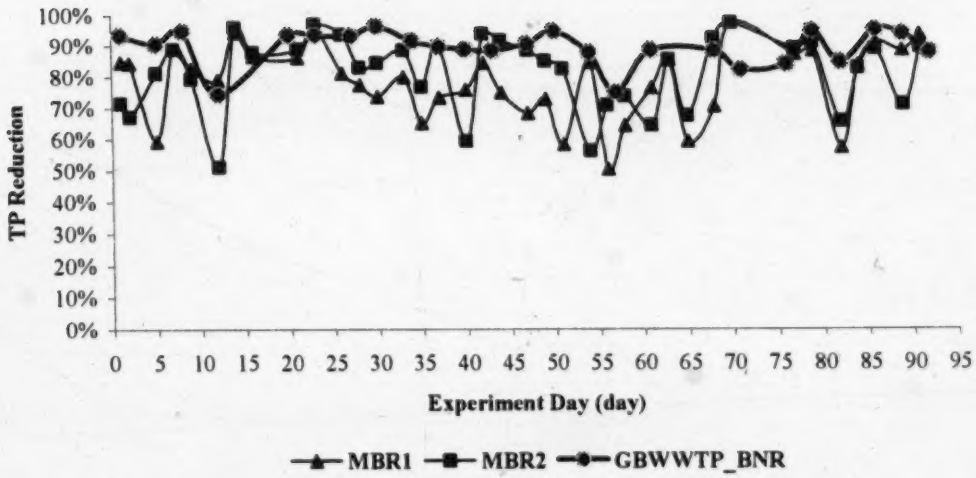

Figure 106. TP reduction of MBR1 and MBR2, as compared to GBWWTP.

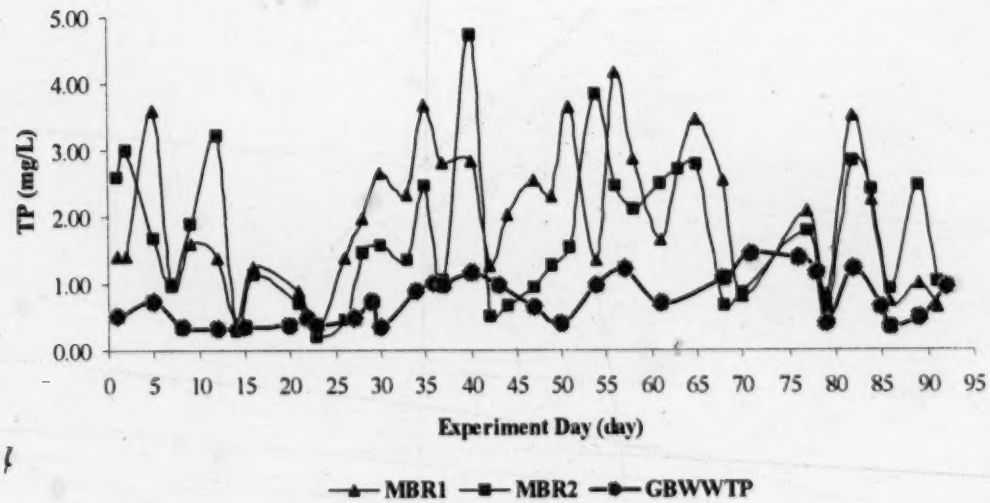

Figure 107. TP concentrations in MBR permeates, as compared to that of GBWWTP final effluent.

During the study, it was observed that TP reduction for BNR-MBR systems was more delicate or sensitive to the processes changes, such as changes of hydraulic loading,

system shutdowns, mixed liquor recirculation rates, biomass concentration changes and aeration conditions. Of these factors, unexpected system shutdowns and reduction of hydraulic loadings were found to have an obvious impact on the TP results. As discussed in section 4.1.14, four unexpected shutdowns happened during the operation. TP reduction efficiencies were all largely reduced after the four shutdowns. The highest residue TP in MBR permeates was always observed on one or two days after the system was shutdown.

When the MBR systems were changed from HRT 6 hours to 8 hours, the TP reduction efficiency was continuously reduced. Over a 12-day operation (HRT 8 hours) period, almost all TP results for both MBRs were higher than GBWWTP's total phosphorus license requirement of 1 mg/L (from day 46 to day 57). The shutdowns or low hydraulic loading may lead to a secondary phosphorus release in the MBR systems. With the underloaded conditions, Bio-P bacteria may start to consume themselves through cell lysis by endogenous respiration after an extended contact time. As a result, the intracellularly stored polyphosphate may be hydrolyzed as an energy source for other bacteria growth, which ultimately led to the release of $O\text{-}PO_4^{3-}$ into the mixed liquor. In this case, the released phosphorus may not be taken up and may remain in the solution leading to an increase of total phosphorus in MBR permeates.

By correlating the TP reduction to the changes of MLSS concentrations, it was observed that TP reduction efficiency deteriorated when the wasting sludge rates were sharply increased and MLSS concentrations were quickly decreased on day 55 to 59 and day 80

to 83 for both MBRs (Figures 108 and 109). It was probably due to insufficient Bio-P bacteria caused by quick biomass loss.

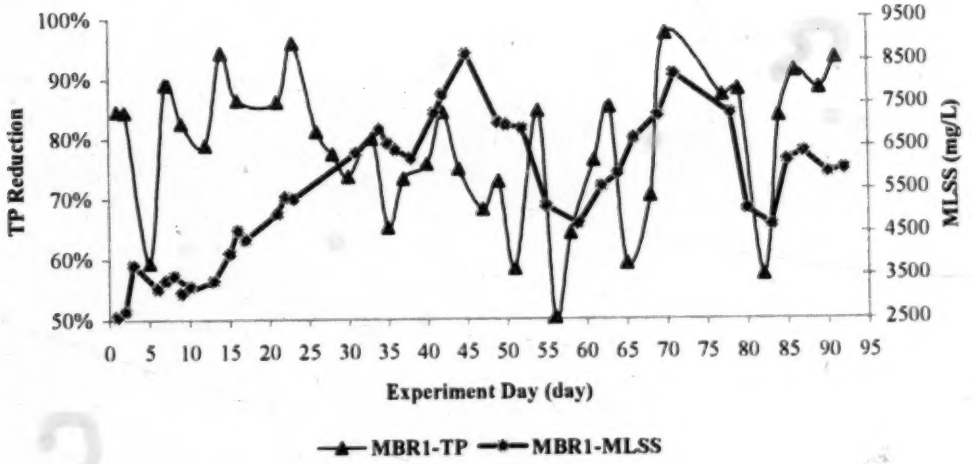

Figure 108. TP reduction and MLSS for MBR1.

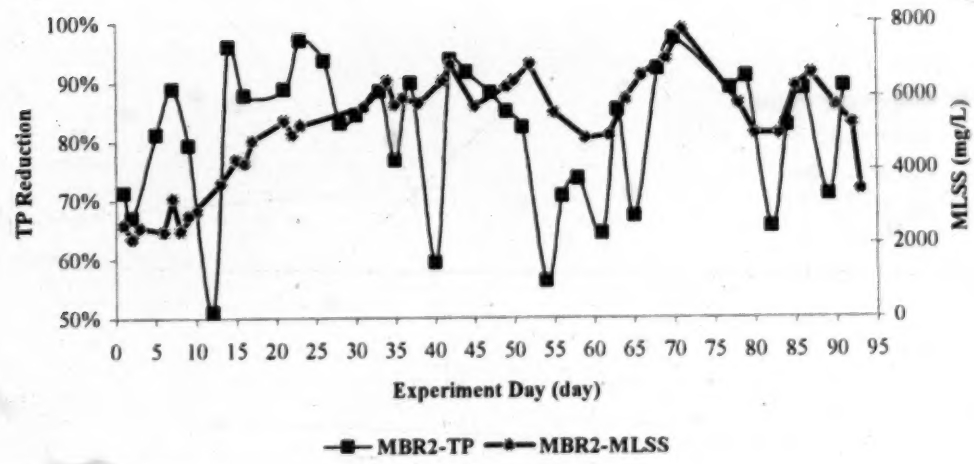

Figure 109. TP reduction and MLSS for MBR2.

It was observed that the system shutdowns and hydraulic loading changes (from 6 hours of HRT to 8 hours of HRT) had an obvious impact on the TP reduction. After the eliminations of those data affected by system shutdowns and loading changes, the TP reduction results are all improved. Of the three different HRT stages, Stage I (HRT=6 hours) performed best. The TP result of MBR2 for stage I was 0.63 mg/L with an average 92.3% of improved TP reduction rate from day 14 to day 45 (Figures 110 and 111). Table 35 lists the 5 data sets removed due to the system shutdowns during a 32-day of stage I operation. Table 36 outlines the comparison of TP reduction before and after the data removed.

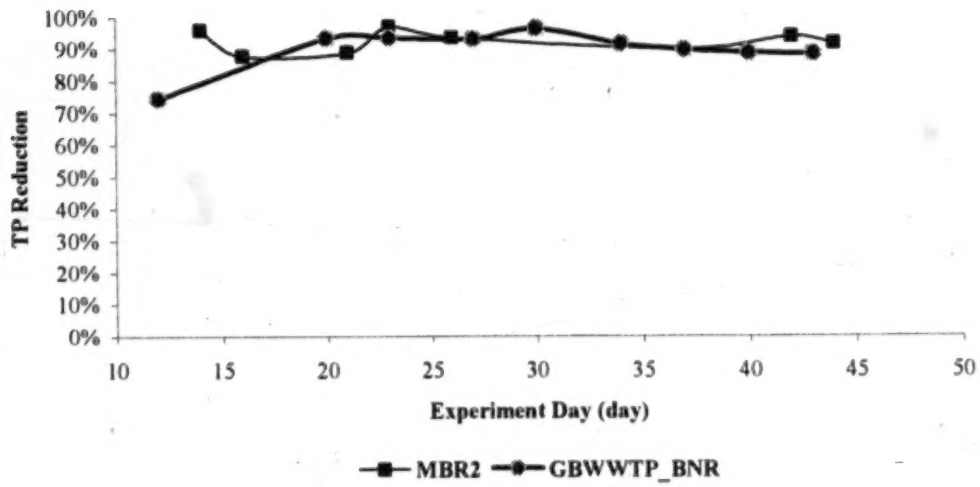

Figure 110. TP reduction rate of MBR2 at stage I, as compared to GBWWTP after data removal.

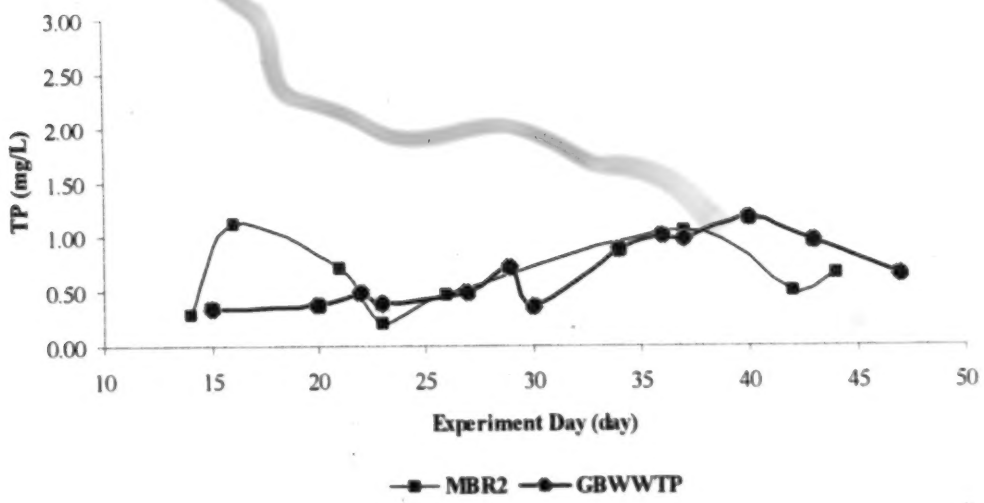

Figure 111. TP in MBR2 permeate at stage I, as compared to GBWWTP after data removal.

Table 35. The eliminated TP data due to shutdowns.

Day	Feed-TP (mg/L)	MBR1-TP (mg/L)	MBR2-TP (mg/L)	Reasons for data removal
28	8.67	1.96	1.47	Shutdown 22 hrs, Day 27 _PE line block
30	10.00	2.64	1.56	Aeration Turn off & on , cell 24
33	11.60	2.33	1.34	Shutdown 3 hrs, Day 32_Power failure
35	10.54	3.68	2.46	MT level down, aeration reduced
40	11.69	2.84	4.74	Shutdown 15 hrs, Day 38&39 PW failure

Besides the operational factors, the limitation on aeration mixing control for MBR reactors was believed to have a significant impact on the overall performance of biological phosphorus removal. There were 12 aerobic cells in each MBR bioreactor. In order to simplify the complexity of installing the mechanical mixing devices for 12 cells in each MBR bioreactor, aeration in each cell was designed for not only providing the dissolved oxygen but also providing the sufficient mixing. Although each cell was

equipped with a mini air valve to control the aeration, the reduction of DO contradicted with the efficiency of mixing. This design limited the control of DO in returned mixed liquor to pre-anoxic zone and anoxic zone.

Table 36. The comparison of TP reduction before and after the eliminations of shutdown data for MBR1 and MBR2.

Stages	MBR1 Permeate TP (mg/L)	TP Reduction rate	MBR2 Permeate TP (mg/L)	TP Reduction rate	HRT (hours)
	Before any data removal				
Stage I	1.83	80.6%	1.28	87.0%	6
Stage II	2.80	66.8%	2.01	76.5%	8
Stage III	1.93	80.2%	1.83	81.3%	4
	After shutdown data removal				
Stage I	1.29	84.6%	0.63	92.3%	6
Stage II	2.46	71.0%	1.89	78.0%	8
Stage III	1.60	84.1%	1.52	85.1%	4

Since the returned sludge was withdrawn from cell 24, which was next to membrane tank, reducing the aeration in cell 24 led to a flow shortcut from cell 23 to recycle tubing inlets, which limited the reduction of DO in the returned mixed liquor. On the other hand, the less mixing may largely extend the retention time of some sludge in cell 24 and may possibly cause a secondary release of phosphorus. Without DO control, the excessive DO in the returned mixed liquor as well as nitrate, functioning as electron acceptor, out competed for the oxidation of bsCOD. The consequent bsCOD consumption by partial nitrification and denitrification reduced the acetate production by the fermentation of

bsCOD. The limited acetate production prohibited the PHB formation in the PAOs and ultimately reduced the efficiency of the biological phosphorus removal. The bio-P bacteria in anoxic and aerobic zones utilize the energy released from the oxidation of PHB stored in its cell to uptake the soluble orthophosphates to form polyphosphate bonds for cell growth.

Due to limited acetate production, some released phosphorus may not be taken-up because the orthophosphate release may not be associated with acetate uptake and PHB storage in PAOs for later oxidation. PO_4^{3-}-P profiling test showed that the high PO_4^{3-}-P concentrations occurred in anaerobic zones were not always coupled with the high TP reduction. There may have other factors to affect the TP reduction efficiency. However, the overall high phosphorus release in the anaerobic zone indicated a better biological phosphorus reduction. This was shown by the TP reduction performance for MBR1 and MBR2. MBR2 with higher PO_4^{3-}-P concentrations in anaerobic zone had a better TP reduction efficiency than MBR1.

In NH_3-N profiling test (Section 4.2.1.3), NH_3-N reduction of 65% in MBR1 pre-anoxic zone and 48% in MBR2 anaerobic zone certainly indicated that besides the dilution effect, some nitrification and NH_3-N assimilation also occurred. The competition for bsCOD consumption by nitrifying organisms led to the reduced bsCOD available for PAOs bacteria and ultimately prohibited PHB formation in PAOs. Due to the reliability of TOXN test methods for the mixed liquor (Section 4.2.1.4), TOXN profiling test results were not able to confirm the nitrification occurred in MBR1 pre-anoxic zone and MBR2

anaerobic zone. But in any case, the NH_3-N reduction must be accompanied with bsCOD consumption. Denitrification may also reduce the Bio-P removal efficiency because of the competition for bsCOD. Figures 112 and 113 show the correlation between the Bio-P removal and the denitrification rate. By comparing the Bio-P reduction rates to the denitrification rates, it was observed that most results with the higher denitrification rates were accompanied by the lower Bio-P reduction rates.

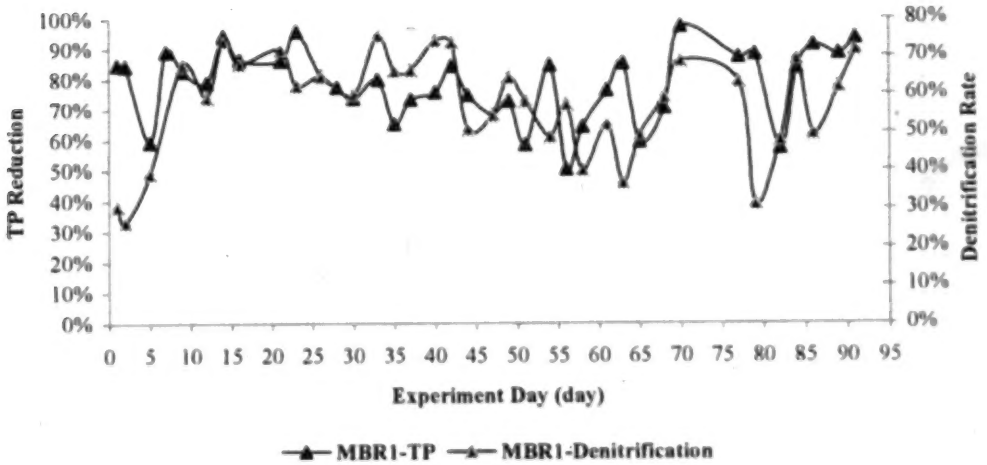

Figure 112. TP reduction rate and denitrification rate for MBR1.

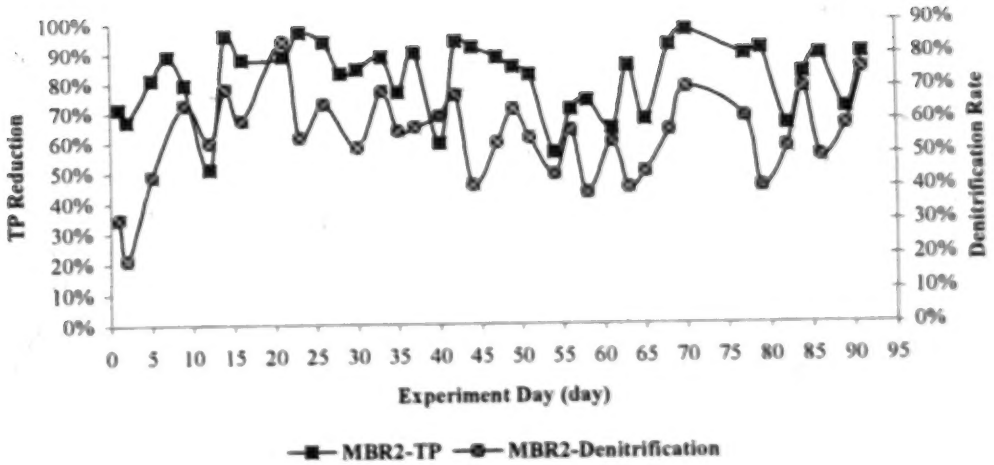

Figure 113. TP reduction rate and denitrification rate for MBR2.

Easily biodegradable organic carbon in the MBR-PE-Feed, as measured by soluble COD, is an important factor for biological phosphorus removal process. If not considering the TP results during startup and shutdowns, most low TP values were concomitant with high sCOD in MBR-PE-Feed (Figures 114 and 115). More sCOD in the influent would certainly enhance the Bio-P reduction efficiency.

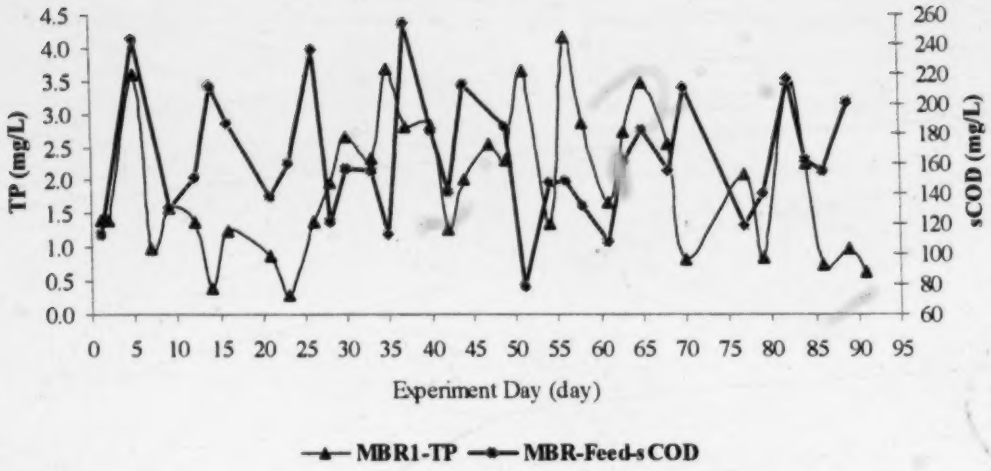

Figure 114. TP of permeate and sCOD of feed for MBR1.

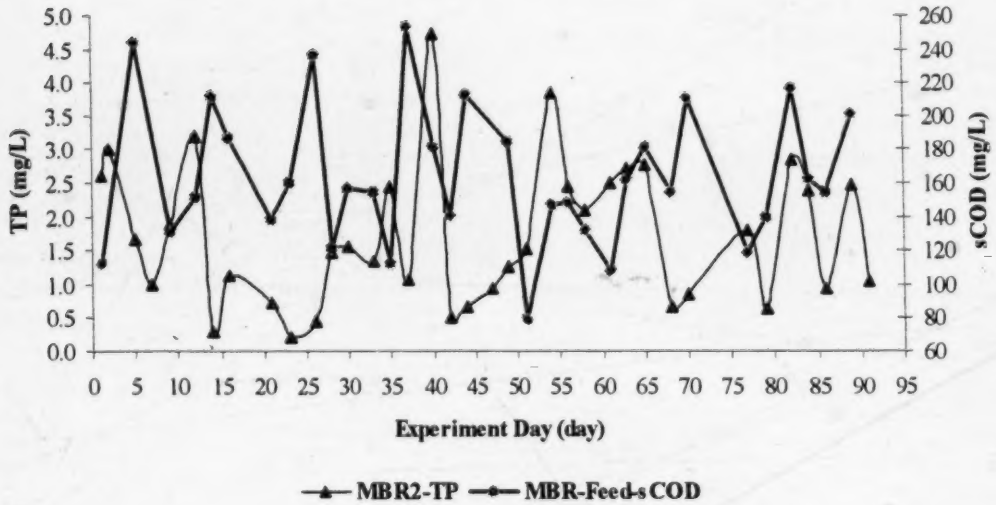

Figure 115. TP of permeate and sCOD of feed for MBR2.

MBR2 had a better performance of biological phosphorus reduction than MBR1. This may probably be explained that due to different process configuration, the returned mixed

liquor (R1) of MBR2 contained much less nitrate as well as oxygen, as compared to the returned mixed liquor (R1) of MBR1, which was drawn from the last cell of aerobic zone. The PAOs in anaerobic zone of MBR2 had better environment to assimilate acetate into PHB storage products with the concomitant release of phosphorus than in anaerobic zone of MBR1 since there were more oxygen and nitrate present in preanoxic and anaerobic zone of MBR1 to compete for bsCOD. It was confirmed by ortho-phosphate (PO_4^{3-}-P) profile analysis. PO_4^{3-}-P concentration in MBR2 anaerobic zone was 100% higher than PO_4^{3-}-P in MBR1 pre-anoxic or anaerobic zone (See section 4.2.1.5). With better acetate consumption and PHB storage in anaerobic zone, the PAOs are encouraged for more ortho-phosphate uptake in aerobic zone and ultimately lead to the removal of phosphorus when the biomass is wasted.

5 Conclusions

The project was designed to improve the treatment efficiency of the previous MBR study and compare process alternatives of GBWWTP process and UCT process using three different HRTs. Two bench-scale (118L) BNR-MBR pilot plants were designed, constructed and operated over a 92 day period. The experiment was carried out at Gold Bar Wastewater Treatment Plant, in parallel to GBWWTP secondary treatment process. The experiment of BNR-MBR pilot plants showed promising results of biological nutrient removal in submerged membrane bioreactors for Edmonton municipal wastewater treatment. The project objectives of this study were fulfilled.

The performance of MBRs indicates that both UCT process and GBWWTP process have similar high reduction efficiency on most of quality parameters, except for the reduction of nitrate / nitrite (TOXN) and phosphorus. MBR1 (GBWWTP process) has better TOXN reduction performance than MBR2 (UCT process). But MBR2 has better biological phosphorus reduction efficiency than MBR1 for Edmonton municipal wastewater.

No obvious differences were indicated on different HRT treatment efficiencies for most of quality parameters, including TSS, BOD_5, COD, TKN, NH_3-N, total coliform, fecal coliform and turbidity. They were all treated at similar high reduction rates of HRT 4, 6 and 8 hours. But the experiment of HRT of 6 hours indicated the best performance of biological phosphorus reduction and denitrification for both MBR1 and MBR2. Particle count result even indicated a comparable quality of permeate to deionized water. The

result of almost 100% coliform reduction presented a great disinfection ability and stability of the ultrfiltration membranes.

The overall performance of the bench scale BNR-MBR pilot plant was well above the performance of the full scale of GBWWTP BNR system (Table 37).

Table 37. Permeate quality of MBRs, as compared to the combined final effluent of GBWWTP over the after-startup period (Day 14-92).

Quality Parameter	Unit	MBR1		MBR2		GBWWTP	
		Mean	Reduction rate	Mean	Reduction rate	Mean	Reduction rate
TSS	mg/L	0.8	99.5%	0.8	99.5%	6.7	94.3%
BOD_5	mg/L as O2	<2	>99.0%	<2	>99.1%	5.0	96.7%
COD	mg/L as O2	24.3	94.4%	24.0	94.5%	41.5	86.9%
TKN	mg/L as N	1.0	98.3%	1.05	98.2%	11.1	73.1%
NH_3-N	mg/L as N	0.0	99.9%	0.1	99.8%	7.8	65.8%
TOXN	mg/L as N	12.5	N/A	13.3	N/A	9.7	N/A
TN	mg/L as N	12.91	73.7%	13.4	72.7%	21.5	48.3%
TP	mg/L as P	1.3	84.6%	0.6	92.3%	0.7	89.4%
Total Coliform	CFU/100 mL	2		6		N/A	N/A
Fecal Coliform	CFU/100 mL	1		1		N/A	N/A
Turbidity	NTU	0.117	N/A	0.117	N/A	N/A	N/A

Note: TP reduction data was only taken from stage I (Day 14-45) with elimination of shutdown data.

The new design of the BNR-MBR systems was successful. The new bench-scale BNR-MBR pilot plants present great improvement of biological phosphorus reduction and nitrogen reduction to satisfy the new limits. In terms of phosphorus removal, UCT process may be more suitable for the treatment of Edmonton municipal wastewater. The BNR-MBR experiment indicates that the MBR technology, coupled with biological

nutrient removal configuration, is one of the feasible technologies in future applications for Edmonton wastewater advance treatment. With the strict limits imposed on effluent discharges and the growing interests in wastewater reuse, this BNR-MBR technology offers even more promising solutions and sees more bright future in wastewater treatment industry.

6 Recommendations

After the operation, the experiment equipment was dismantled in a way that the BNR-MBR experiment can be easily set up again in order to carry on for further studies of any wastewater treatment. In order to further improve the efficiency and stability of denitrification and phosphorus reduction, some recommendations are outlined as following:

1) The mixing function of the aeration in aerobic cells should be replaced using mechanical mixers installed in aerobic cells. The mixing motors should be equipped with longer shafts other than that of non-aeration mixing motors as each aerobic cell must be left open for aeration. If possible, high-speed applicable motors are recommended, as one 40 rpm motor may not provide sufficient mixing for one aerobic cell.
2) Free from the mixing function, the aeration in aerobic cells should be reduced to provide the dissolved oxygen between 1 to 2 mg O_2/L with high-to-low DO distribution along aerobic zone. The DO concentration in the last cell of aerobic zone should be controlled at about 0.5 mg/L to prevent excessive dissolved oxygen from being recycled to the non-aeration zones and inhibiting denitrification and biological phosphorus removal processes.
3) The mixed liquor backflow to feed tank should be avoided by careful handling of mixed liquor recirculation. The feed autosampler should be programmed to a minimum batch volume and maximum intervals to avoid the influence on the PE level of the feed tank.

4) The operational strategy of the BNR-MBR pilot plants should focus on HRT of 6 hours with longer operation period as HRT of 8 hours may lead to underloaded condition and HRT of 4 hours may increase the operational difficulties of both recirculation pumps and membrane modules.

BNR-MBR technologies present a promising solution for wastewater reuse applications. The high consistent permeate quality results from the experiment indicate that BNR-MBR technology may probably be the best practical technology option for future upgrade of the Gold Bar Wastewater Treatment Plant. A large scale of BNR-MBR study may be necessary to find the optimum design parameters for future full-scale BNR-MBR implementation.

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Appendix A – MBR Control Software and Hardware

The MBR control software was developed by contract consultant Roy using National Instruments Corp. Labview 7.0 for Microsoft Windows 2000 operating system. The software was based on the modification of the similar software used for Roy Guest's experiment.

The software was easier to learn and control with friendly operation windows. The data collected was simultaneously copied into excel file for record. New files were created at time zero on midnight. One included data from feed temperature, two DO meters and suction pressure for MBR1 and MBR2, respectively. The other included the open and close time of the permeate autosamplers for MBR1 and MBR2. The data logging time intervals can be changed at anytime. The suction pressure and DO curves were simultaneously displayed on the computer screen for monitoring purpose. Some photo examples of the software interfaces are illustrated in appendix B.

One desktop computer equipped with AD (Analog to Digital) board was used for instrumentation control. A 24-volts AC power supply and a connection box were united as automation box (See Appendix B) to transmit the site signal to the AD board. The AD board has 16 physical channels for analog-digital conversion as listed below table 38.

Table 38. Signal channel distributions of AD board.

Channels	Connected signals
0	MBR1 Suction Pressure
1	Not used
2	DO meter #1 for MBR1
3	DO meter #2 for MBR1
4	Level Float for MBR1
5	MBR2 Suction Pressure
6	Not used
7	DO meter #1 for MBR2
8	DO meter #2 for MBR2
9	Level Float for MBR2
10	Not used
11	Solenoid valve#1 for MBR1 permeate autosampling
12	Conductivity#1 for tracer test
13	Conductivity#2 for tracer test
14	Solenoid valve#2 for MBR2 permeate autosampling
15	Temperature

The signal reading was taken and shown as the average of 8 readings per second. The time intervals for actual data logging can be defined and inputted into the control program at anytime.

Appendix B – Some Experiment Photos

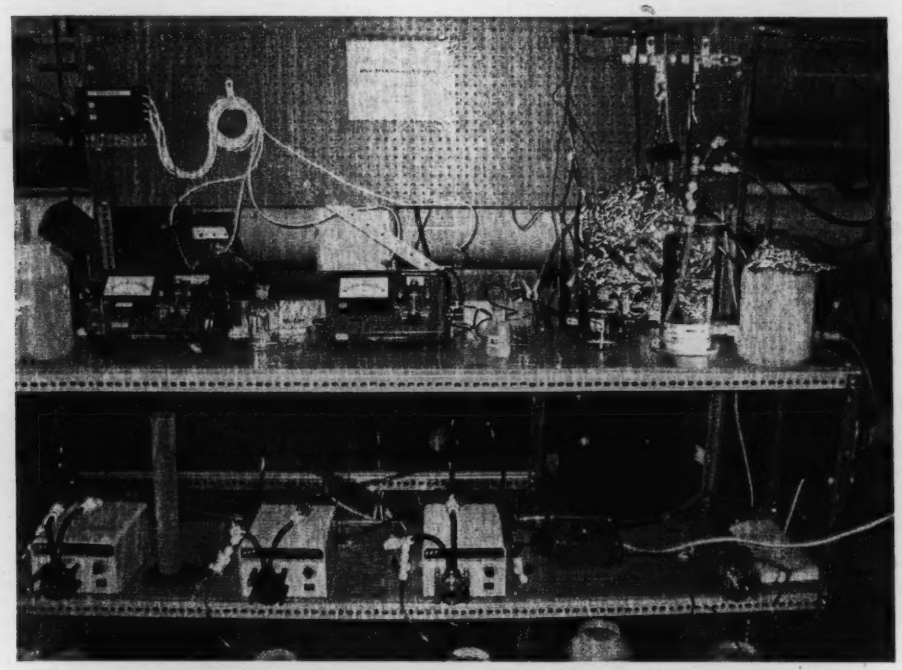

Figure116. MBR1 operation on day 41.

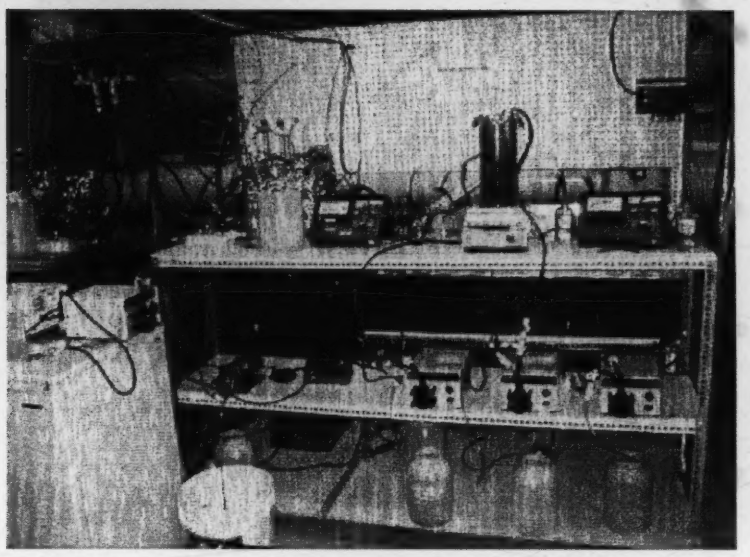

Figure 117. MBR2 operation on day 78.

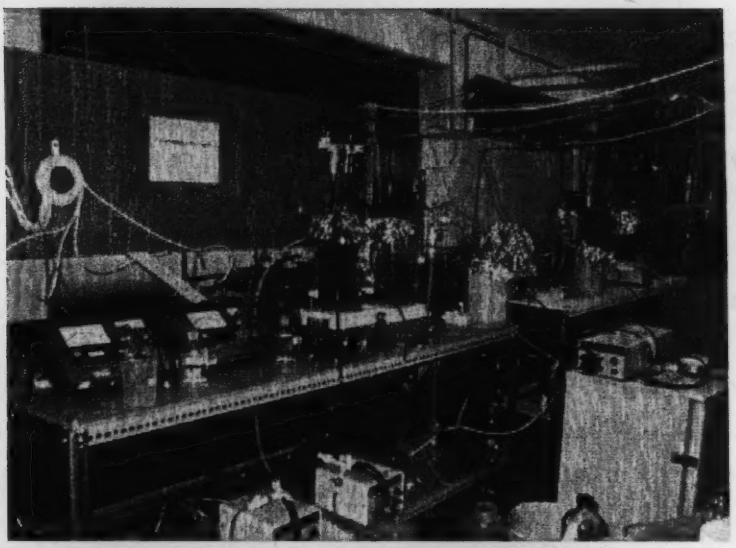

Figure 118. MBR operation on day 56.

Figure 119. Visual permeate quality on day 46.

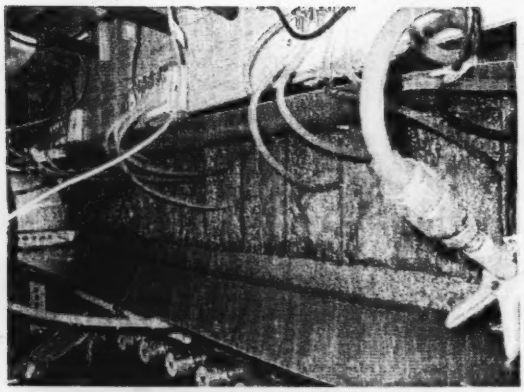

Figure 120. Foaming on the surface of MBR1 aeration zone on day 78.

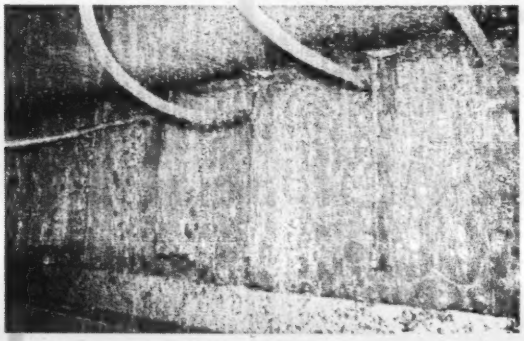

Figure 121. Foaming reduced on day 80.

Figure 122. ZW-10 membrane module after drain on May 3, 2004.

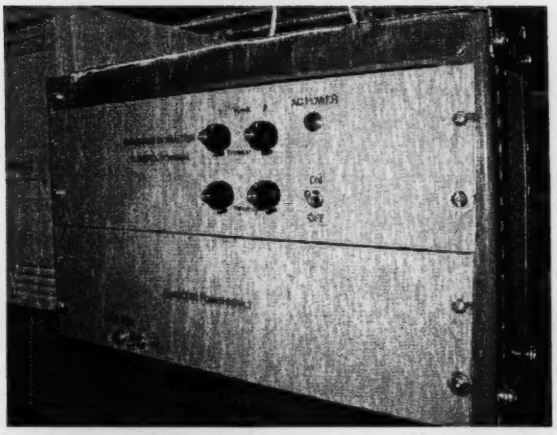

Figure 123. 24V DC power supply & automation connection box.

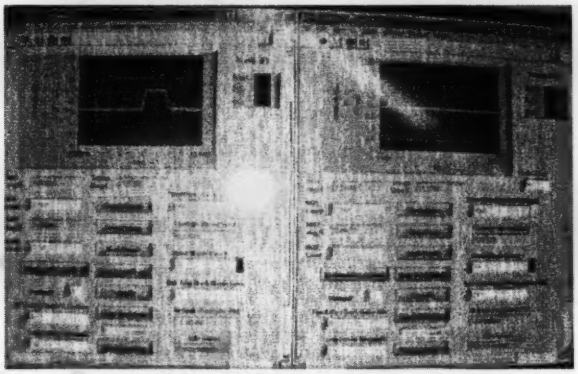

Figure 124. The interface display of Control software.

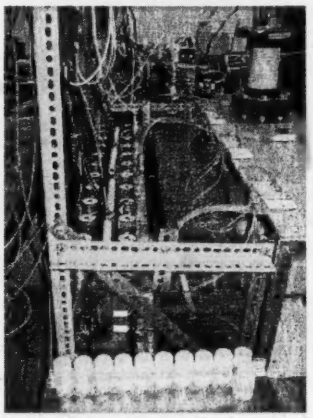

Figure 125. MBR tracer test on Dec 17, 2003.

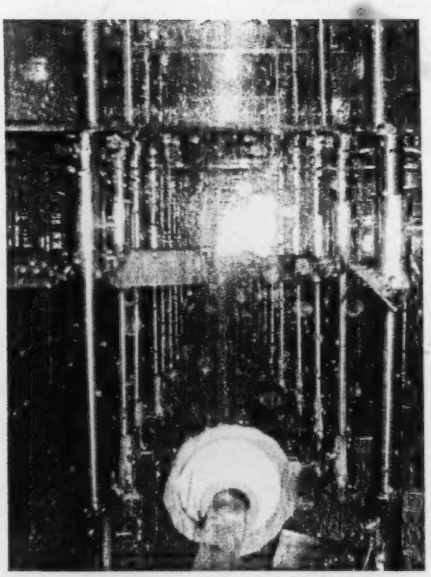

Figure 126. Impellers in non-aeration zone on water test run on January 25, 2004.

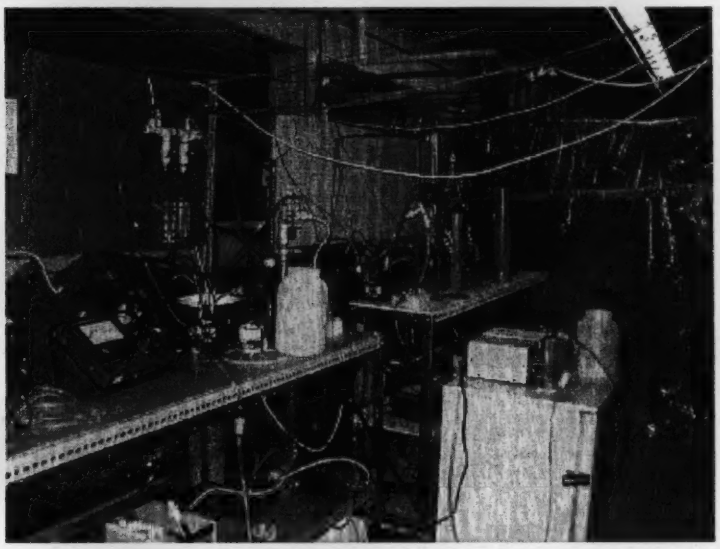

Figure 127. The water test run of the BNR-MBR pilot plants on January 25, 2004

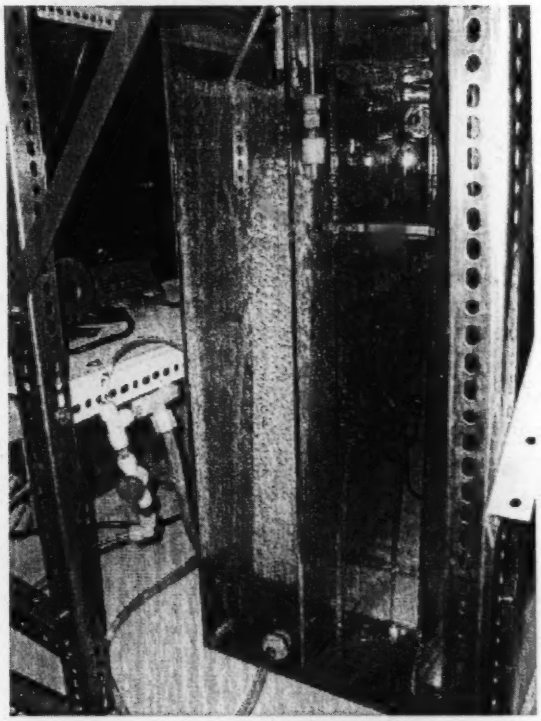

Figure 128. MBR2 membrane tank during the water test run.

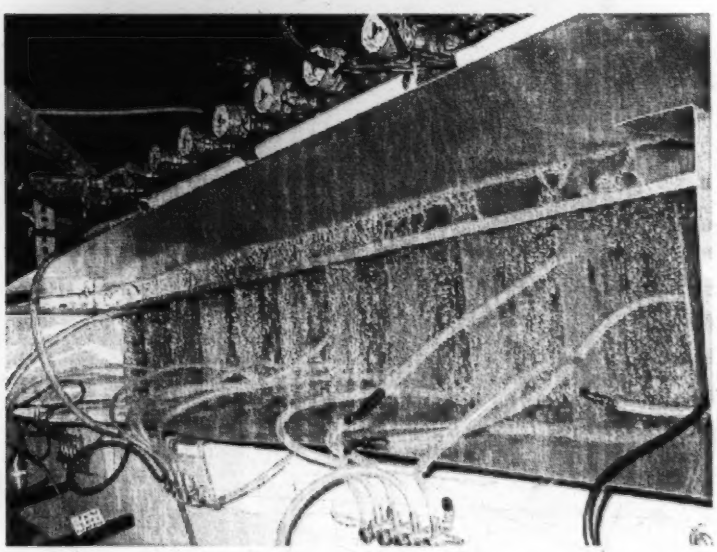

Figure 129. MBR2 aeration zone during the water test run.

Appendix C – Summary of BNR-MBR Operation Record

Table 39 summarizes the all the major operation events recorded in the experiment field log over the entire BNR-MBR experiment period. Some operation events may not be included due to heavy workload on the experiment site.

Table 39. The summary of operation record over the experiment period

Date	BNR-MBR Operation Events (January 2004 – April 2004)
20031210-20031218	During December 10 - 18, tracer tests were completed for both units for a hydraulic time of 4, 6 and 8 hours. P/B: 15min/30s; 1P:-1.63psi; 2P:-1.56psi
20040124-20040126	Water test run, flow rate calibration, sampler Calibration, instrument adjustment
20040127 Day1	**Start up for both BNR-MBR units.** The mixed liquor of non-aeration zone was taken from anaerobic zone of No.10 tank. The mixed liquor of aeration zone was taken from the 4th path of No. 10 tank. Unit 1 started at 14:45. Unit 2 started at 17:00. **Permeate flowrate: 480 mL/min. HRT: 4hours. R1=0.5Q, R2=1.5Q, R3=2.5Q.** Observation: Light Foaming ; Measure taken: Reduce aeration
20040128 Day2	Production/Backpulse: 7.5min/15seconds; 1P: -1.77 psi; 2P: -1.76 psi; Turbidity meter not work, pH meter not function; Sampling: Feed 1.5L/hour; Permeate: 50 second/15min
20040130	Calibration Waste Sludge flowrate: 1&2WS: 4.2mL/min.
20040131 Day 4	1R2 pumphead tube leak, replaced @10:00 a.m.; 2MT half full, filled with PE@10:15 a.m. 2MT air diffuser blocked, increased air to blow it through; Re-set up the level control float. 1P: -2.229 psi; 2P: -2.19 psi **New condition: reduced permeate flowrate to 325 mL/min (1P&2P)** **1P: -1.51psi; 2P: -1.64psi; R1=0.73Q; R2=2.21Q; R3=3.38Q; HRT=6hours @19:50**
20040201 Day5	Foaming in MT R_cells; Feed sampling: 12:00-17:00 1L/hour for 6 batches Permeate sampling: 16:00-21:00 250ml/15min for 24 batches (6L)
20040202 Day 6	Permeate Calibration: 1P: 327.5 mL/min; -1.43 psi; 2P: 315 mL/min; -1.53psi Clean top foam layer of 1NA zones from 11:30 to 13:00
20040203	1R3 pump head tube replaced
20040204 Day 8	Feed autosampler not function, repaired. Scum in 1AN recycle cell reach top. Raised PE level due to scum blocking flow.
20040205 Day 9	MLSS Profile analyses. DO meter calibration by using BOD dilution water from Goldbar lab **Adjust R1 (both units) from 240 mL/min (0.73Q) to 340 mL/min (1Q)**
20040206 Day 10	**Adjustment @ 10:30:** **1R3 from 1040 mL/min (3.2Q) to 1200 mL/min (3.69Q);** **2R3 from 720 mL/min (2.21Q) to 1000 mL/min (3Q);** **2R3 from 1000 mL/min (3.07Q) to 1200 mL/min (3.69Q);** **Measure effective: Unit 1: 116 L – 119.96 L; Unit 2: 114 L – 117 L** **Unit 2 R2 Inlet changed from MT bottom to AO cell 24 @ 18:25** **Reduced DO of cell 24. Placed DO meter 21 @ cell 24** **Unit 1 R2 to AO cell 24. Reduced DO of cell 24. DO meter 11 not work.** **Placed DO meter 12 @ cell 24** **Up to now Turbidity meter and pH meter not function**
20040207 Day 11	**Unit 1 R1 inlet changed from MT bottom to AO cell 24 @9:30-11:00** Cleaned NA zones of unit 2. 13 More mixing impellers added. Set sampling permeate time: 17:00 – 22:05
20040209 Day 13	Cleaned Unit 1 and added more mixing impellers DO meter 12 contaminated Observation: Unit 2 suction pressure reduced to -1.29 psi

20040210 Day 13	**Added one 1.2 m air diffuser to each MT R_cell @ 11:00.** One motor in 1AN zone got stuck and was fixed. 2P suction pressure continue to drop to -1.10 psi Air foaming in both MT R_cells rose.
20040211 Day 15	Flow rate Calibration: WS flowrate: 1WS: 3mL/min; 2WS adjusted from 2.9mL/min to 3mL/min Permeate flowrate: 1P 320 mL/min, -1.65 psi; 2P 310 mL/min -1.06 psi
20040212 Day 16	Aeration flow rate: Unit 1 Unit 2 MT 70 SCFH ($2m^3/h$) 70 SCFH($2m^3/h$) AO 55-60 SCFH 55-60 SCFH ($1.57-1.71m^3/h$) DO cell 24 3.64 mg O_2/L DO cell 22 5.67 mg O_2/L MT 7.8 mg O_2/L
20040213 Day 17	R1/unit 1 pump head tube leaked and changed pump head. Unit 2 suction pressure continued to drop to -0.88 psi Calibrated WS flowrate @ 15:48 4 mL/min for both units
20040215 Day 19	Calibrated 2WS: 4mL/min. Changed membrane of DO meter 11 and 12. Suction pressure: Unit 1: - 1.64 psi; Unit 2: -0.74 psi
20040217 Day 21	Recycle flow rate adjustment: Unit 1: R3 line blocked, changed tube from 720 mL/min to 1590 mL/min(5Q) R2 line blocked, changed inlet valve and tube from 680 mL/min (2.125Q)to to 1050 mL/min (3.28Q). R1 checked @ 390 mL/min (1.2Q). Unit 2: R3 from 1380 mL/min (4.45Q) to 1580 mL/min (5Q). R2 / unit 2: Changed tube, from 860 mL/min(2.64Q) to 960 mL/min(3Q).
20040218 Day 22	Calibrated R2/unit2 from 960 mL/min to 1075 mL/min (3.35Q) @11:54 R1/unit 2: 345 mL/min (1.07Q) DO: cell24/unit2: 3.6 mg O_2/L; cell 18/unit2: 5.4 mg O_2/L
20040219 Day 23	Unit 1: -1.63 psi; Unit 2: -0.385 psi DO cell18/unit2: 5.7 mg O_2/L; cell24: 4.7 mg O_2/L (DO meter 21)
20040220 Day 24	Unit 1: -1.66 psi; Backpulse: 1.31 psi; Unit 2: -0.30 psi; Backpulse: 2.46psi Profile analyses
20040221 Day 25	9:00 – 20:20 Cleaned Unit 1 NA zones. Added more mixing impellers Cleaned Unit 2 NA zones. Added more mixing impellers
20040223 Day 27	**PE line blocked. Unit 2 stopped for 22 hours from 14:41 on Feb22 to 12:32 on Feb 23 due to low PE influent. Turned off waste pump @9:30. Reduced R3/unit2. Stopped unit 1 from 11:00 to 12:11. Cleaned PE cells for both units. Used air hose (120 psi) to blow through PE line.** DO cell24/unit24: 3.7 mg/L Recycle calibration: Unit1: R1=340 mL/min(1Q); R2=1000 mL/min(3Q); R3=1620mL/min(5Q) Unit2: R1=340 mL/min(1Q); R2=1075 mL/min(3.3Q); R3=1620 mL/min(5Q)
20040224 Day 28	Unit1: -1.61 psi; Unit2: -0.29 psi DO cell24/unit2: 4.2 mg O_2/L. Changed DO meter probe membranes and Calibrated. **Turned off the aeration of cell24 for both units to reduce DO for recycling. Reduced aeration for cell 17-cell 23.** DO @unit2: cell24: 0 mg O_2/L; cell13-23: 4-6 mg O_2/L; MT: 7-8 mg O_2/L DO@unit1: cell24: 0 mg O_2/L; cell 13-23: 4-6 mg O_2/L: MT: 7-8 mg O_2/L Changed pump tube: R1/unit2
20040225	Unit 1: -1.60 psi BP: 1.30 psi. Unit 2: -0.35 psi, BP: 2.33 psi Air foaming scum in both AN& AE zones increased quickly since the air was turned off for

	cell24. Permeate NO3 increased. **Turned on aeration of cell 24 for both units @14:51** **Reduced aeration for all aeration cells for about 30%** DO measurement: Unit1: cell 13-23: 4-5 mg O_2/L; cell 24: 3.4 mg O_2/L; MT: 7.7 mg O_2/L Unit2: cell 13-23: 4.7-5.4 mg O_2/L; cell24: 3.9 mg O_2/L; MT: 7.5 mg O_2/L
20040226 Day 30	Unit 1: -1.61 psi; Unit 2: -0.39 psi DO: cell24/unit1 2.5 mg O_2/L; cell13/unit1: 4.42 mg O_2/L Cell24/unit2: 3.68 mg O_2/L; cell13/unit1: 4.7 mg O_2/L
20040227 Day 31	Unit1: -1.58 psi- -1.64psi; Unit2: -0.30 psi – -0.39 psi DO cell24/unit1: 5.13 mg O_2/L, cell13/unit1:4.13 mg O_2/L DO cell24/unit2: 4.8 mg O_2/L; cell 4.31 mg O_2/L
20040228 **Day 32**	**Due to GBWWTP power failure, computer shut down for 3 hours (from 6:59 to 10:00).** **Using high permeate flow rate (500 mL/min) provide PE quickly.** DO higher during shutdown, probably due to less food to be consumed.
20040301 Day33	**Unit 1: -1.31 to -1.36 psi BP: 1.6psi;** Unit2: -0.01 to -0.06 psi BP: 2.67psi DO cell13/unit1: 4.7 mg O_2/L; cell24/uni1: 2.6 mg O_2/L Cell13/unit2: 4.56 mg O_2/L; cell24: 2.5 mg O_2/L
20040302 Day 35	Unit 1: -1.31 to -1.37 psi BP: 1.61psi;Unit 2: -0.01 to – 0.07 psi BP: 2.66 psi Reduced DO on Unit2 cell24, cell 23, cell 22, cell21; cell24 from 2.6 mg O_2/L to 1.76 mg O_2/L; Aeration from 55SCFH to 50 SCFH for both units; MT from 75 SCFH to 70 SCFH for both units; MT level became low due to scum blocking the path in non-aeration zones. Reduced R3:unit1 from 1650 to 1520 mL/min, unit 2 from 1620 mL/min to 1580 mL/min.
20040303 Day 36	Unit 1: -1.35 to – 1.39 psi; BP: 1.63 psi ;Unit2: -0.109 to -0.135 BP: 2.63 psi; cell13/unit1: 4.4 mg O_2/L, cell24: 1.32 mg O_2/L; cell 13/unit2: 4.23 mg O_2/L, cell24: 1.40 mg O_2/L; R3 back to unit 1: 1650 mL/min unit2:1620 mL/min @11:00; Cleaned scum of unit 1: 1300-1500 and unit 2 from 15:10 to 16:30, mixing impellers adjusted. Reduced R3 again unit1 1650 to 1520, unit2: 1620 to 1580
20040304 Day 37	Unit1: -1.36 to -1.40 psi BP 1.63 psi; Unit 2: -0.16 to -0.20 psi BP2.58 psi; Increased R3 back to unit 1650 mL/min and unit 2: 1620 mL/min. DO @ 18:13 cell13/unit1: 3.9 mg O_2/L; cell24/unit1:0.71 mg O_2/L; cell24/unit2: 0.72 mg O_2/L; cell13/unit2: 4..18 mg O_2/L; MLSS profile analyses; **MLSS level decreased due to influent line becoming narrow. Shook feed tube to remove the dirt attached to tubes, the MLSS level increased @19:27**
20040305 Day 38	MLSS level increased over top impellers. Due to better mixing and low DO, a better denitrification should be observed in next samples.
20040306 **Day 39**	**Due to GBWWTP power failure, systems shut down for 15 hours** from 18:54 on Mar 5 and recovered @11:35 on Mar 6. DO cell13/unit1: 3.97 mg O_2/L, cell24/unit1: 1.50 mg O_2/L; cell13/unit2: 3.83 mg O_2/L, cell24/unit2: 1.12 mg O_2/L. Changed pump tube R3/unit1, R1/unit2. MLSS level decreased, cleaned aeration cell openings and the level recovered.
20040308	Unit 1: - 1.39 to 1.63 to -1.34 psi; Unit2: -0.25 to 2.51 to -0.20 psi; DO unit1: 4.12 mg O_2/L /unit1, 1.60 mg O_2/L /cell24, Unit2: 3.9 mg O_2/L /cell13, 0.95 mg O_2/L /cell24.
20040309 Day 42	Unit1: -1.37 psi; Unit2: -0.25 psi; DO unit1: 4 mg O_2/L /unit1, 2.29 mg O_2/L /cell24, Unit2: 3.57 mg O_2/L /cell13, 1.16 mg O_2/L /cell24. Good mixing on top of NA zones. **Feed sampling: 24 samples 12:00 to 18:00, 250mL/15min**
20040310	Unit1: -1.40 psi; Unit2: -0.28 psi. Good mixing @ surface of all NA cells. Increased DO of recycle cells to 1.61 mg O_2/L /unit1, 1.60 mg O_2/L /unit 2.
20040311	Unit1: -1.36 psi, Unit2: -0.36 psi; **DO increased.** DO unit1: 4.68 mg O_2/L /unit1, 4.25 mg O_2/L /cell24, Unit2: 3.75 mg O_2/L /cell13, 4.89 mg O_2/L /cell24. DO @19:21. MLSS profile analyses.
20040312 **Day 45**	Unit1: -1.44 to 1.66 to -1.40 psi; Unit2: -0.45 to 2.40 to -0.36 psi; DO unit1: 3.5 mg O_2/L /unit1, 2.82 mg O_2/L /cell24, Unit2: 3.5 mg O_2/L /cell13, 2.74 mg O_2/L /cell24. Calibrated flow rates of recycle and permeate. **Changed operating condition from HRT 6 hours to HRT 8 hours and calibrated flow rates accordingly.** Permeate: 244 mL/min; R1=1Q,

	R2=3Q, R3=5Q @17:07. Sampling schedule: Feed 10:00 – 17:30, 30 samples, 200 mL/15 min. Permeate: 16:30 to 23:55, 200 mL/15 min.
20040313 day 46	Unit1: -1.00 psi; Unit2:-0.22 psi. P/B: 7.5 min/15s. DO unit1: 4.5 mg O_2/L /unit1, 4.4 mg O_2/L /cell24, Unit2: 3.9 mg O_2/L /cell13, 3.78 mg O_2/L /cell24. Changed pump head tubing: R3/unit2. **Opened aeration in unit2 MT R_cell @15:05.**
20040315 Day 48	Unit1: -1.02 psi and Unit2: -0.30 psi. DO unit1: 4.37 mg O_2/L /unit1, 1.51 mg O_2/L /cell24, Unit2: 3.08 mg O_2/L /cell13, 2.27 mg O_2/L /cell24. Unit 2 & Unit1 MLSS level decreased. Used air blow through the influent line to recover. **For the first time in operation, slight foaming was observed in AO zone of unit1, probably due to HRT increased and less food supplied.**
20040316 Day 49	Unit1: -1.01 psi, Unit2: -0.37 psi. DO unit1: 4.6 mg O_2/L /unit1, 2.23 mg O_2/L /cell24, Unit2: 3.2 mg O_2/L /cell13, 1.77 mg O_2/L /cell24. Foaming decreased. Good mixing in NA zones. Motor changed for cell 8/unit2.
20040317 Day 50	Unit1:-1.02psi; Unit2:-0.47 psi. DO @9:33 unit1: 5 mg O_2/L /unit1, 0.55 mg O_2/L /cell24, Unit2: 3.37 mg O_2/L /cell13, 4.36 mg O_2/L /cell24. Aeration valves were fully opened@10:17 for all cells. Recycle calibration: 5Q, 3Q and 1Q. DO @14:47 unit1: 4.74 mg O_2/L /unit1, 4.59 mg O_2/L /cell24, Unit2: 3.94 mg O_2/L /cell13, 5.15 mg O_2/L /cell24.
20040319 Day 52	Unit 1: -1.03 psi and Unit2: -0.53 psi DO unit1: 4.6 mg O_2/L /unit1, 4.76 mg O_2/L /cell24, Unit2: 4.15 mg O_2/L /cell13, 4.05 mg O_2/L /cell24. Recirculation adjusted: **R2/Unit1: from 3Q to 4Q; R2/unit2: from 3Q to 4Q.** Reduced aeration of cell 21, 22, 23 and 24 of both units. Cell24/unit1: 3.9, cell 24 /unit2: 3.5 mg O_2/L.
20040320 Day 53	DO unit1: 4.46 mg O_2/L /unit1, 5.64 mg O_2/L /cell24, Unit2: 3.99 mg O_2/L /cell13, 4.79 mg O_2/L /cell24. Reduced DO of cell 17 to 24. adjusted two times. DO @18:28 unit1: 4.8 mg O_2/L /unit1, 2.19 mg O_2/L /cell24, Unit2: 3.56 mg O_2/L /cell13, 3.29 mg O_2/L /cell24. **Opened aeration of unit 1 MT R_cell @12:31.** Calibrated R3/unit1 to 5.2Q, R3/unit2 to 5.3Q @19:12. Slight foaming observed @AO zones. Increased the aeration. MT to 70 SCFH, AO from 50 to 70 SCFH. DO unit1: 4.7 mg O_2/L /unit1, 5.04 mg O_2/L /cell24, Unit2: 3.9 mg O_2/L /cell13, 3.7 mg O_2/L /cell24.
20040322 Day 55	**Cell13/unit1 foaming covered fully**. DO unit1: 5.1 mg O_2/L /unit1, 6.63 mg O_2/L /cell24, Unit2: 3.75 mg O_2/L /cell13, 5.0 mg O_2/L /cell24. **Added additional container for R1/unit1@12:30 and R2/unit2@17:24 to reduce DO.** DO unit1: 5.24 mg O_2/L /unit1, 0.82 mg O_2/L /cell24, Unit2: 3.35 mg O_2/L /cell13, 2.05 mg O_2/L /cell24. Activated sludge observed by Microscope by Grace: Low filamentous activities, low protozoa activities, No worms found, No rotifers found.
20040323 Day 57	**Added container for R2/unit1@13:00. Blow feed line@14:00.** DO unit1: 5.15 mg O_2/L /unit1, 0.19 mg O_2/L /cell24, Unit2: 2.99 mg O_2/L /cell13, 1.84 mg O_2/L /cell24. Air diffuser rose to top in MT R_cell/unit2, weight added to place at bottom again. **Stopped systemfor 17 hours @20:12 due to PE line out of service (Goldbar Tank No.1).** Stopped wasting sludge@21:20. Obvious foaming observed @cell13/unit1 and cell13/unit2. Added PE manually to both units and cleaned foaming@23:00. Samples collected only from 16:30 to 20:00 for permeate with decreased feed.
20040324	**Unit 1 MT half full due to MT/AO line blocked.** Recovered @11:05. Cleaned feed cells. **Restarted systems @13:03.** Using 460 mL/min (equal to high flux 30 L/m^2/hr). **Changed operating condition and Adjusted permeate flowrate@19:11 to 490 mL/min (HRT 4hours).** Unit1: -3.23psi to 2.53psi to 2.41 psi; Unit2: -2.45 psi to 3.01 psi to -1.85psi. Recycle didn't change.
20040325 Day 58	Unit 1: -3.489 to 2.66 to -2.67 psi; Unit2: -2.726 to 2.99 to -2.18 psi. R2/unit1 overflowed about 3L due to safety line misplace on the bench. Overall foaming reduced after restarted. Cleaned foaming of both units. **Calibrated permeate flow rate: 1P=463 mL/min. 2P=460mL/min.** R3/unit1: 4.3Q. R2/unit1: 4Q. R1/unit1: 1.06Q; R3/unit2: 4.7Q, R2/unit2: 4Q.R1/unit2: 1.08Q @18:07. Production/backpulse: 225seconds/15 seconds or 3.75 min/15s. Sampling schedule: Feed: 13:30 to 17:30, 1P&2P: 17:00 to 21:00.
20040326 Day 59	Unit1: -2.92 to 2.44 to -2.43psi. Unit2: -2.19psi. DO unit1: 5.4 mg O_2/L /unit1, 0.17 mg O_2/L /cell24, Unit2: 2.84 mg O_2/L /cell13, 0.09 mg O_2/L /cell24. **Foaming observed in both**

	MTs and AO cells: cell13, 14, 15, 21/unit1; cell13, 14, 15, 18, 19/unit2. Quality of permeate not expected since recycle adjustment, feed tank cleaned, MLSS level reduced and increased, biomass removed. Air diffusers cleaned for cell 13 of both units. Cell 13/unit 2 DO increased from 2.6 to 4.12 mg O_2/L.
20040327 Day 60	Unit 1: -2.94 to 2.45 to -2.54 psi. Unit2: -2.28 to 2.83 to -2.16psi. DO unit1: 5.08 mg O_2/L /unit1, 2.14 mg O_2/L /R, Unit2: 3.54 mg O_2/L /cell13, 2.96 mg O_2/L /R (true value after shaking DO probe). **Temperature check:** Feed tank 13 °C (0.6 higher than outside PE channel 12.4°C). AO/unit1: 15.9°C,AO/unit2: 15.7°C (2-3 higher than outside head of AO tank 13°C). Effective volume check: Unit 1=116L (HRT=4.2 hours); Unit2=120 L (HRT=4.3hours).
20040329 Day 62	Unit1:-3.01 to 2.55 to -2.60 psi; Unit2: -.264 to 2.96 to -2.29 psi. MLSS level decreased. Changed production/backpulse @10:15 from 225S/15S to 450S/15S. Overall foaming reduced. Cell 13, 14, 24/unit1 and cell 13/unit2 still have foaming. DO unit1: 4.51 mg O_2/L /unit1, 1.07 mg O_2/L /R, Unit2: 3.05 mg O_2/L /cell13, 1.01 mg O_2/L /R
20040330 Day 63	Unit 1: -3.34 to 2.64 psi; Unit 2:-2.96 to 3.09 psi. Changed membrane for DO meter No.1/unit2: DO @12:27 unit1: 4.59 mg O_2/L /unit1, 2.10 mg O_2/L /R, Unit2: 5.95 mg O_2/L /cell14, 2.61 mg O_2/L /R, cell 24/unit2: 4.23 mg O_2/L. cell13, 14, 21, 24/unit1 cell13/unit2 still foaming but got better. Reduced aeration for both units: AO from 70 SCFH to 50 SCFH. MT: 70 SCFH. Reduced aeration of cell 21, 22, 23, 24 for both units. DO @13:31 unit1: 4.34 mg O_2/L /unit1, 1.14 mg O_2/L /R, Unit2: 4.93 mg O_2/L /cell13, 1.48 mg O_2/L /R
20040331 Day 64	Unit1: -3.35 to 2.69 psi; Unit 2: -2.96 to 3.15 psi. DO unit1: 4.72 mg O_2/L /unit1, 0.89 mg O_2/L /R, Unit2: 4.56 mg O_2/L /cell13, 1.03 mg O_2/L /R. Foaming observation: cell 13 of both units fully covered. Cell14, 19, 21, 23 and 24/unit1, cell18, 21, 23, 24/unit2 still some. Unit2 less than unit1. Changed R3/unit2 tubing.
20040401 Day 65	Unit1: -3.44 to 2.77 psi; Unit2: -3.03 to 3.33 psi. Fully opened cell 21 to 24 aeration @18:42. **Black spot observed in some corners.** Scum accumulated in NA zones. Cell 21 air diffuser found vertical against, led to scum accumulated in the other side of the cell wall. Profile analyses. Some scum left over the top of AO cells.
20040402 Day 66	Cleaned up unit 2 NA zones. Adjusted impellers. Cleaned up air diffusers of cell13/unit2, cell15/unit2. Foaming appeared after cleaning due to more air bubbles. High aeration (200 SCFH) for unit2 for very short time.
20040403 Day 67	Unit1: -3.61 to 2.92 psi; Unit2: -3.17 to 3.40 psi. DO @14:36 unit1: 4.25 mg O_2/L /unit1, 0.03 mg O_2/L /R, Unit2: 4.59 mg O_2/L /cell13, 1.36 mg O_2/L /R. Clean up unit1 NA zones. Increased aeration from 50 SCFH to 70 SCFH @13:00. Some foaming observed in AO zones. Changed pump head tubing R3/unit1 @14:31 (5.1Q).
20040405 Day 69	Unit1: -3.73 to 2.96 psi; Unit2: -3.38 to 3.48 psi. DO unit1: 3.89 mg O_2/L /unit1, 0.01 mg O_2/L /R, Unit2: 4.51 mg O_2/L /cell13, 0.76 mg O_2/L /R. MLSS level decreased. Changed R3/unit2 tubing to increase from 3.5Q to 4.78Q. Calibration: R2/unit2 3.65Q. R1/unit2: 1Q. R2/unit1: 3.5Q.
20040407 Day 71	Unit1: -3.62 to 3.08psi, Unit2: -3.31 psi. DO unit1: 2.95 mg O_2/L /unit1, 0.51 mg O_2/L /R, Unit2: 3.84 mg O_2/L /cell13, 2.14 mg O_2/L /R. **More foaming accumulated first time covered fully of all cells in both units except for MT.** R2/unit2 container foaming scum accumulated to the top of the container and overflowed a little(probably 500 mL)@9:00. Increased unit2 aeration from 70 SCFH to 200 SCFH @10:22, more foaming occurred, then changed back to 80 SCFH@11:30. **Foaming became severe.** Stoped influent to clean influent line from 16:01 to 16:35.
20040408 Day 72	Unit1: -3.77 to 3.09 psi. Unit2: -3.35 to 3.62 psi. DO unit1: 3.05 mg O_2/L /unit1, 1.41 mg O_2/L /R, Unit2: 5.03 mg O_2/L /cell13, 1.62 mg O_2/L /R(true value). Tightened R2/unit2 line suction head to prevent air suction. **Changed Production / Backwash time from 450s/15s to 225s/15s@15:06.**
20040409 Day 73	Backpulse disabled from 15:28 on April8 to 12:13 on April 9 (suction pressure from -3.10 psi to -3.57 psi). Recycle container: R2/unit1: 1000 – 1250 ml. R1/unit1: 800 ml, R2/unit2: 1000ml. Increase aeration from 65 to 80 SCFH (unit1), from 70 to 80 SCFH(unit2). DO unit1: 3.28 mg O_2/L /unit1, 1.73 mg O_2/L /R, Unit2: 5 mg O_2/L /cell13, 2.83 mg O_2/L /R.

20040411 Day 75	Unit 1: -3.67 to 2.84 psi; Unit2: -3.37 to 3.30 psi. DO unit1: 2.89 mg O_2/L /unit1, 0.97 mg O_2/L /R, Unit2: 4.9 mg O_2/L /cell13, 2.27 mg O_2/L /R. **Thickened foaming fully covered each AO cell and MLSS level decreased in both units.** Foaming rose again only short time after cleaned up.
20040412 Day 76	**Unit2 stopped from 16:59 to 19:32 for 2.5 hours due to MT/AO line blockage leading to empty MT. Heavy thick foaming.** Changed pump head tubing for R3/unit1, R2/unit1 and R3/unit2. Cleaned up heavy foaming and foaming formed again shortly after the clean up in both AO zones. DO unit1: 3.45 mg O_2/L /unit1, 3.34 mg O_2/L /R, Unit2: 5.57 mg O_2/L /cell13, 4.40 mg O_2/L /R.
20040414 Day 78	Unit1:-3.52 to 3.37 psi, Unit2: -3.71 to 3.50psi. DO unit1: 3.02 mg O_2/L /unit1, 1.91 mg O_2/L /R, Unit2: 5.32 mg O_2/L /cell13, 3.40 mg O_2/L /R. **Changed production /Backpulse to 450s/15s@9:02. Foaming still covered each cell. Increased waste flow rate to reduce foaming: 4mL/min to 16mL/min@11:10. Fine air bubbles observed in unit2 permeate line and may cause high particle count.** Unit 2 foaming became less @16:58. Unit1 cell24, 23, 22 still heavy foming.
20040415 Day 79	Unit1: -4.03 to 3.50psi; Unit2: -4.25 to 3.58psi. Foaming became less in both units but cell24/unit1 still heavy. R1/unit1 overflowed through safety line back to cell 24. After mixed the bottom of cell 20, 21 24/unit1, foaming suddenly increased even after clean up @18:09. However, overall foaming reduced after high sludge wasting rate 16mL/min.
20040416 Day 80	Unit1: -4.20 to 3.40 psi; Unit2: -4.10 to 3.62 psi. Suction pressure not increased due to solids reduced. Unit1 Cell 20, 21, 24 still heavy foaming. Rest cells and unit2 foaming greatly reduced. Reduced aeration from 80 SCFH to 60 SCFH. Slight white air bubbles foaming formed on top of both MTs.
20040417 Day 81	Unit1: -3.52 to 3.28 psi; Unit2: -3.52 to 3.65psi. DO unit1: 2.78 mg O_2/L /unit1, 3.50 mg O_2/L /R, Unit2: 5.03 mg O_2/L /cell13, 3.77 mg O_2/L /R. Foaming were greatly reduced. Reduced WS flow rate from 16 mL/min to 8 mL/min@14:40.
20040419 Day 83	Unit1: -3.75 to 3.42 psi; Unit2: -3.82 to 3.68 psi. Slight foaming still appeared in some cells. Reduced WS flow rate from 8mL/min to 4mL/min@11:33. Calibrated recycle flow rate and changed tubing. DO unit1: 2.25 mg O_2/L /unit1, 3.42 mg O_2/L /R, Unit2: 4.54 mg O_2/L /cell13, 3.80 mg O_2/L /R.
20040421 Day 85	Unit1: -3.70 to 3.56 psi; Unit2: -3.88 to 3.76psi. Foaming almost gone. Reasnons: Certain filamentous microorganism produced due to scarce food or conditions greatly changed, to a certain level and start to dominate and grow, then foaming formed by rising air bubbles. Reduced solids, meantime also increased food supply, unfavourable conditions for filamentous microorganism to bring down foaming to a certain level, normal activated sludge dominated, then foaming eliminated most. DO unit1: 1.25 mg O_2/L /unit1, 2.68 mg O_2/L /R, Unit2: 3.86 mg O_2/L /cell13, 2.58 mg O_2/L /R. Cell24/unit1 still have heavy scum plus some foaming@12:00.
20040422 Day 86	Running smoothly. Unit1 cell 23, 24 and unit2 cell 23 still had some scum. Paper filtration for all MLL profile samples, including blank DI water. **Unit1 pressure transducer lost function @14:51.** Cleaned up scum twice.
20040423 Day 87	Unit1 cell 23, 24 and unit2 cell23 foaming again. Probably due to residual filamentous microorganism grow again. Increase WS from 4mL/min to 6 mL/min to reduce foaming.
20040424 Day 88	Production/Backpulse: 225s/7.5s. Unit1 cell 22, 23, 24 some foaming, Unit2 cell22, 23 foaming. Cleaned up foaming.
20040426 Day 90	@8:20, unit1 cell 22, 23 foaming cover full cell and thick. Unit 2 cell 17, 18, 19, 20, 22, 23 foaming cover full cells and thick. Backpulse malfunction, shutdown the computer and restart computer again. Increased WS flow rate from 4mL/min to 17 mL/min @12:00 for both units to reduce foaming. R2 unit2 pump stopped and new pump replaced. Unit2 foaming become more severe. Clean foaming and reduced WS flow rate from 17mL/min to 4mL/min@21:30.
20040428 Day 92	Foaming in both units greatly reduced. No obvious foaming in unit1. Unit2 cell 22 and 23 still have some foaming. It's unexpected to have foaming reduced since there were more foaming in the evening of April26 when WS flow rate turned back from 17mL/min to 4

	mL/min. Production/Backpulse: 225s/7.5s.
20040429 Day 93	Foaming in both units almost gone except unit2 still have some in cell 22 and 23 but greatly reduced. Sample collected @ 04:00 to 08:00 for 1P&2P. 00:05 to 04:00 for feed. Due to the biomass loss and different sample collection time. This set of sample was only for reference. MLSS samples collected @ 8:00 for Activated sludge analyses (ASA). Permeate flow rate calibration: unit1 415 mL/min, unit 2 370mL/min. Started to stop experiment @10:12 by increased WS flowrate to the maximum unit1 96mL/min. 76mL/min.
20040430	Stopped the system. Drain the mixed liquor. Started to dismantle and clean the equipment.

Appendix D – Raw Data (GBWWTP Lab Reports)

The reports of analytical results for BNR-MBR project by GBWWTP laboratory are listed in table 40 –53 as they were delivered.

THE CITY OF Edmonton

Gold Bar Wastewater
Treatment Laboratory
10977 - 50 Street
Edmonton, Alberta T6A 2E9

Accredited for specific tests by the Standard Council of Canada (SCC) and the Canadian Association for Environmental Laboratories (CAEAL), and complies with the ISO 17025 requirements.

Project ID: **BNR-MBR** Gold Bar File No:53-042-002-028

Client's Name:	**Albert liu**	Approved by:	**Geoff Heise**
Location:	**University of Alberta**		**Research and Development Scientist**
Email:	**jianguo@ualberta.ca**	Date Released:	**20040210**
Phone Number:	**(780) 467-8677**	Project Coordinator:	**Geoff Heise**
Report Number:	**20040209**	Project Leader:	**Vanessa Luick**
Sample Disposal:	**20040223**		

Results relate only to the samples tested.

Table 40. GBWWTP lab report for MBR (January 27 to January 28, 2004).

SOURCE	DATE	Goldbar ID	TESTS							
			COD mg/L	CO-F-M cfu/100mL	CO-T-M cfu/100mL	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L
F20040127	20040127	200401605	451	-	-	35.0	53.4	0.222	9.12	102
1P20040128	20040128	200401603	33	<1	<1	12.3	15.6	12.1	1.40	nd
2P20040128	20040128	200401604	31	<1	<1	14.1	17.6	10.1	2.61	nd
1AO20040128	20040128	200401606	-	-	-	-	-	-	-	2570
2AO20040128	20040128	200401607	-	-	-	-	-	-	-	2520
Limit of Detection			2.0/5.0	1	1	0.013	0.032	0.006	0.016	6.0

Table 41. GBWWTP lab report for MBR (January 29 to February 6, 2004).

SOURCE	DATE	Goldbar ID	TESTS													
			COD mg/L	COD-H-sol mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	pH -	Turb. NTU
2A00129040000	20040129	200401654											2156			
1A00129040111	20040129	200401655											2704			
F013004	20040129	200401739	368	371			29.0	54.2	< .006	9.12	110					
1P013004	20040129	200401740	25.1				13.2	16.0	8.15	1.42	1.2					
2P013004	20040129	200401741	27.4				18.3	23.0	5.18	3.00	0.6					
1AO013004	20040130	200401742											3764			
2AO013004	20040130	200401743											2456			
F0202040000	20040201	200401903	320	113	tntc	tntc	35.2	53.6	<.006	8.84	91					
P1202040000	20040201	200401904	25.3		44	<1	1.15	1.90	20.3	3.59	0.8					
P20202040000	20040201	200401905	20.6		48	<1	4.77	8.64	15.0	1.66	0.8					
1A00202040000	20040202	200401906											3228			

2AO0202040000	20040202	200401907											2340			
1A00203040000	20040203	200401956											3404			
2A00203040000	20040203	200401957											3260			
1P020404	20040203	200402025	21.5				0.474	1.81	13.7	0.98	<0. 6				7.4	~0.25
2P020404	20040203	200402026	23.6				2.05	5.27	11.3	1.00	<0. 6				7.7	~0.11
1AO020404	20040204	200402027											3512			
2AO020404	20040204	200402028											2372			
1PR020504000	20040205	200402097											1676	1504		
1AE02054000	20040205	200402098											1520	1360		
1AN02054000	20040205	200402099											2864	2372		
1AO02054000	20040205	200402100											3112	2524		
1MT02054000	20040205	200402101											3800	3068		
1MR02054000	20040205	200402102											3876	3128		
2AE02054000	20040205	200402103											976	884		
2AN02054000	20040205	200402104											2304	1904		
2AO02054000	20040205	200402105											2780	2268		
2MT02054000	20040205	200402106											3256	2604		
2MR02054000	20040205	200402107											3336	2732		
1P020604	20040205	200402179	16.4				0.317	pending	10.9	pending	<0.6					
2P020604	20040205	200402180	24.6				1.68	pending	10.4	pending	<0.6					
F020604	20040205	200402181	524	244			34.9	pending	0.006	pending	136	102				
1P020604	20040206	200402182			25	<1										
2P020604	20040206	200402183			90	<1										
F020604	20040206	200402184			38×10^6	2.2×10^6										
1AO020604	20040206	200402185											3260			
2AO020604	20040206	200402186											2912			
	Limit of Detection		2.0/5.0	2.0/5.0	1	1	0.013	0.032	0.006	0.016	0.6	-	-	-	-	0.05

Table 42. GBWWTP lab report for MBR (February 7 to February 14, 2004).

SOURCE	DATE	Goldbar ID	TESTS												
			BOD	COD	COD-H-sol	N-NH3	N-TKN	N-TOX	TP	TSS	VSS	TSS-P	VSS-P	CO-T-M	CO-F-M
			mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	cfu/100mL	cfu/100mL
1PO20904	20040208	200402354	<2	18.5		0.052	0.96	10.9	1.38	<0.6					
2PO20904	20040208	200402355	<2	23		0.097	1.02	12.4	3.21	<0.6					
FO20904	20040208	200402356	177	357	131	27.0	37.9	<0.006	6.56	94.0	70.0				
1AO020904	20040209	200402357										3390			
2AO020904	20040209	200402358										3640			
1P021104	20040210	200402486	1.6	17.6		0.020	1.04	6.02	0.40	1.2					
2P021104	20040210	200402487	<2	22.2		0.027	1.01	6.94	0.29	0.1					
F021104	20040210	200402488	248	411	151	23.3	39.8	0.033	7.06	115					
1AO21104	20040211	200402489										4030			
2AO21104	20040211	200402490										4290			
1P021104	20040211	200402491												12	<1
2P021104	20040211	200402492												8	<1
F021104	20040211	200402493												27×10^6	3.5×10^6
1PR021204	20040212	200402557										2820	2320		
1AE021204	20040212	200402558										2740	2270		
1AN021204	20040212	200402559										3660	2920		
1AO021204	20040212	200402560										4550	3510		
1MT021204	20040212	200402561										6370	4860		
2AE021204	20040212	200402562										1820	1570		
2AN021204	20040212	200402563										2980	2480		
2AO021204	20040212	200402564										4200	3370		
2MT021204	20040212	200402565										5100	4020		
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1

Table 43. GBWWTP lab report for MBR (February 15 to February 28, 2004).

SOURCE	DATE	Goldbar ID	TESTS													
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL	Colour-H Pt-co
1AO021704	20040217	200402898										4950	3840			
1MT021704	20040217	200402899										6910	5280			
2AO021704	20040217	200402900										5350	4020			
2MT021704	20040217	200402901										6410	4790			
1P021804	20040217	200402994	<2	20.4		0.013	0.95	7.93	0.88	<0.6						
F021804	20040217	200402996	~124	508	187	28.2	39.2	0.085	6.40	140	114					
2P021804	20040218	200402995	<2	21.2		<0.013	0.93	4.39	0.71	<0.6						
1P0218040000C	20040218	200402997												8	<1	
2P0218040000C	20040218	200402998												<1	<1	
F0218040000C	20040218	200402999												47×10^6	1.9×10^5	
1AO21804	20040218	200403000										5340	4090			
2AO021804	20040218	200403001										5000	3740			
1MT021804	20040218	200403002										6360	4830			
2MT021804	20040218	200403003										6110	4570			
1PR021904	20040219	200403117										3230	2610			
1AE021904	20040219	200403118										3100	2540			
1AN021904	20040219	200403119										4870	3860			
1AO021904	20040219	200403120										5290	4070			
1MT021904	20040219	200403121										6400	4920			
2AE021904	20040219	200403122										2440	1970			
2AN021904	20040219	200403123										4220	3220			
2AO021904	20040219	200403124										5240	4000			
2MT021904	20040219	200403125										6270	4740			
1P022004	20040219	200403205	~7.6	20		0.026	0.89	9.20	0.30	0.7						
2P022004	20040219	200403206	<2	14.5		0.024	0.91	10.9	0.22	~1						
F022004	20040219	200403207	268	457	138	24.5	38.0	0.008	7.34	169	109					

1AO022004	20040220	200403208										2800	2120			
2AO022004	20040220	200403209										2610	1910			
1P022304	20040222	200403399	<2	29.4		0.066	1.03	11.7	1.38	<0.6						
2P022304	20040222	200403400	2.2	23.1		0.059	1.01	11.5	0.47	1						
F022304	20040222	200403401	174	365	160	33.4	7.34	0.006	7.34	142	104					
1PR022404	20040224	200403450										8840	8050			
1AE022404	20040224	200403451										10700	9870			
1AN022404	20040224	200403452										10400	9220			
1AO022404	20040224	200403453										12300	10700			
1MT022404	20040224	200403454										24300	22400			
2AE022404	20040224	200403455										2160	1680			
2AN022404	20040224	200403456										4060	3000			
2AO022404	20040224	200403457										5080	3670			
2MT022404	20040224	200403458										5860	4300			
1P022504	20040224	200403574	<2	pending		0.034	1.11	10.396	1.96	3						44
2P022504	20040224	200403575	<2	pending		0.050	1.12	12.829	1.47	1.1						37
F022504	20040224	200403576	273	pending	pending	35.0	49.2	0.026	8.67	112	96					
1P022504C	20040225	200403577												<1	<1	
2P022504C	20040225	200403578												3	<1	
F022504C	20040225	200403579												31×10^6	1.9×10^6	
1AO022504	20040225	200403580										2950	2600			
2AO022504	20040225	200403581										2240	1930			
1P022704	20040226	200403732	<2	pending		0.042	1.19	12.3	2.64	<0.6						34
2P022704	20040226	200403733	<2	pending		0.057	1.15	14.7	1.56	<0.6						38
F022704	20040226	200403734	274	pending	pending	30.9	51.7	0.008	10.0	132	116					
1AO022704	20040227	200403735										6360				
2AO022704	20040227	200403736										5720				
1MT022704	20040227	200403737										7760				
2MT022704	20040227	200403738										6920				
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1	-

Table 44. GBWWTP lab report for MBR (February 29 to March 6, 2004).

SOURCE	DATE	Goldbar ID	TESTS													
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL	Colour-H Pt-co
1P030104	20040229	200403902	<2	22		0.033	1.23	12.6	2.33							31
2P030104	20040229	200403903	<2	20		0.04	1.13	15.8	1.34							28
F030104	20040229	200403904	212	408	157	51.5	64.6	0.006	11.6							
1AO030104	20040301	200403905										6910	5420			
1MT030104	20040301	200403906										8580	6740			
2AO030104	20040301	200403907										6420	4960			
2MT030104	20040301	200403908										7560	5830			
1PRO30204	20040302	200403975										4940	4000			
1AE030204	20040302	200403976										4900	4060			
1AN030204	20040302	200403977										5500	4100			
1AO030204	20040302	200403978										6570	4930			
1MT030204	20040302	200403979										7920	5890			
2AE030204	20040302	200403980										3840	3290			
2AN030204	20040302	200403981										4750	3730			
2AO030204	20040302	200403982										5770	4470			
2MT030204	20040302	200403983										7060	5410			
1P030304	20040302	200404092	<2	20		0.02	0.99	12.7	3.68	1						39
2P030304	20040302	200404093	<2	23		0.04	1.12	16.2	2.46	1						
F030304	20040302	200404094	226	447	157	37.8	59.1	0.027	10.5	136	108					
1PO030304C	20040303	200404095												<1	1	
2PO030304C	20040303	200404096												28	1	

F030304C	20040303	200404097												59 x 10^6	2.5 x 10^6	
1AO030304	20040303	200404098										6430	5020			
2AO030304	20040303	200404099										5960	4520			
1P030504	20040304	200404239	~2.9	24.4		0.02	1.05	11.8	2.80							
2P030504	20040304	200404240	~2.0	26.0		0.06	1.10	14.6	1.06							
F030504	20040304	200404241	346	441	113	35.2	62.6	0.006	10.5							
1AO030504	20040305	200404242										6230	4910			
1MT030504	20040305	200404243										7610	5960			
2AO030504	20040305	200404244										5830	4530			
2MT030504	20040305	200404245										7020	5440			
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1	-

Table 45. GBWWTP lab report for MBR (March 7 to March 13, 2004).

SOURCE	DATE	Goldbar ID	TESTS													
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL	Colour-H Pt-co
1P030804	20040307	200404411	<2	31		0.02	1.06	11.5	2.84							
2P030804	20040307	200404412	<2	31		0.02	1.14	17.1	4.74							
F030804	20040308	200404413	~242	487	254	44.5	72.7	0.07	11.7							
1AO030804	20040308	200404414										7290	5590			
1MT030804	20040308	200404415										6430	4840			
1PR030904	20040309	200404511										4750	3710			

1AE030904	20040309	200404512										4760	3700			
1AN030904	20040309	200404513										6420	4890			
1AO030804	20040309	200404514										7710	5820			
1MT030904	20040309	200404515										9260	6990			
2AE030904	20040309	200404516										2740	2150			
2AN030904	20040309	200404517										4910	3600			
2AO030904	20040309	200404518										6870	5140			
2MT030904	20040309	200404519										8260	6130			
1P031004	20040309	200404615	<2	30		0.019	0.93	7.49	1.27	0.6						
2P031004	20040309	200404616	<2	19		0.003	0.92	9.14	0.51	0.6						
F031004	20040310	200404617	238	470	*pending*	28.6	44.3	0.01	8.11	216	148					
1P031004C	20040311	200404618												<1	<1	
2P031004C	20040311	200404619												5	<1	
F031004C	20040311	200404620												10.8×10^6	$\sim 1.0 \times 10^6$	
1P031204	20040311	200404766	<2	21		<0.013	0.97	9.69	2.02	<0.6						
2P031204	20040311	200404767	<2	23		<0.013	0.97	11.6	0.67	<0.6						
F031204	20040311	200404768	146	363	141	19.7	43	0.01	8.02	154						
1AO031204		200404769										8660	6220			
1MT031204		200404770										5030	3010			
2AO031204		200404771										5740	3270			
2MT031204		200404772										7550	5530			
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1	-

Table 46. GBWWTP lab report for MBR (March 14 to March 20, 2004).

SOURCE	DATE	Goldbar ID	TESTS													
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL	Colour-H Pt-co
1P031504	20040314	200404957	<2	23		<0.013	0.99	14.1	2.55	~0.6						
2P031504	20040314	200404958	<2	24		<0.013	1.06	14.3	0.936	1						
F031504	20040314	200404959	167	350	358	30.9	45.0	<.006	7.19	280	84					
1PR031604	20040316	200405109										3780	2740			
1AE031604	20040316	200405110										3790	2790			
1AN031604	20040316	200405111										5920	4270			
1AO031604	20040316	200405112										7060	4990			
1MT031604	20040316	200405113										8410	6000			
2AE031604	20040316	200405114										2580	1940			
2AN031604	20040316	200405115										4980	3560			
2AO031604	20040316	200405116										6270	4420			
2MT031604	20040316	200405117										7790	5500			
1P031704	20040316	200405194	<2	24		0.039	1.07	12.3	2.29	<0.6						
2P031704	20040316	200405195	<2	23		0.033	1.01	11.9	1.26	<0.6						
F031704	20040316	200405196	194	679	213	34.64	48.5	0.059	8.40	188	152					
1P031704C	20040317	200405197												<1	<1	
2P031704C	20040317	200405198												<1	<1	
F031704C	20040317	200405199												15.3×10^6	1.2×10^6	
1AO031704	20040317	200405200										7010	4960			
2AO031704	20040317	200405201										6440	4480			
1P031904	20040318	200405347	<2	29		0.053	1.05	15.5	3.65	0.6						
2P031904	20040318	200405348	<2	22		0.028	1.00	16.7	1.54	<0.6						
F031904	20040318	200405349	202	364	185	37.1	49.4	0.093	8.77	128	116					
1AO031904	20040319	200405350										6920	4870			
2AO031904	20040319	200405351										6870	4800			
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1	-

Table 47. GBWWTP lab report for MBR (March 21 to March 28, 2004).

SOURCE	DATE	Goldbar ID	TESTS												
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL
1P032204	20040321	200405543	<2	14		0.029	1.06	21.9	4.35	<0.6					
2P032204	20040321	200405544	<2	17		0.023	0.99	20.1	3.84	2					
F032204	20040321	200405545	160	321	79	39.3	49.0	0.047	8.77	108	90				
1PR032204	20040322	200405546										3350	2420		
1AE032204	20040322	200405547										3280	2390		
1AN032204	20040322	200405548										5800	3940		
1AO032204	20040322	200405549										5120	3490		
1MT032204	20040322	200405550										6910	4660		
2AE032204	20040322	200405551										2640	1970		
2AN032204	20040322	200405552										4670	3080		
2AO032204	20040322	200405553										5580	3720		
2MT032204	20040322	200405554										6360	4170		
1P032404	20040322	200405684	<2	24		0.051	0.97	15.2	4.15	1					
2P032404	20040322	200405685	2	30		0.031	1.04	15.2	2.45	<0.6					
F032204	20040322	200405686	154	329	147	35.7	48.5	<.006	8.36	104	88				
1P032604	20040325	200405842	<2	19		0.388	1.49	18.4	2.86	<0.6					
2P032604	20040325	200405843	<2	21		0.793	2.25	18.0	2.11	<0.6					
F032604	20040325	200405844	166	365	148	31.3	-	0.021	-	74	58				
1AO032604	20040326	200405845										4700	3460		
2AO032604	20040326	200405846										4880	3570		
1MT032604	20040326	200405847										5870	4310		
2MT032604	20040326	200405848										5800	4170		
1P032904	20040328	200406066	<2	22		0.021	0.65	15.4	1.66	<0.6					
2P032904	20040328	200406067	<2	28		0.018	0.99	14.8	2.50	<0.6					
F032904	20040328	200406068	162	383	132	32.1	45.6	0.012	7.00	158	108				
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1

Table 48. GBWWTP lab report for MBR (March 29 to April 4, 2004).

SOURCE	DATE	Goldbar ID	TESTS												
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL
1PR032904	20040329	200406069										3200	2310		
1AE032904	20040329	200406070										3200	2380		
1AN032904	20040329	200406071										4710	3380		
1AO032904	20040329	200406072										5570	3950		
1MT032904	20040329	200406073										6400	4540		
2AE032904	20040329	200406074										2180	1610		
2AN032904	20040329	200406075										4510	3170		
2AO032904	20040329	200406076										4970	3550		
2MT032904	20040329	200406077										6010	4220		
1P033104	20040330	200406224	<2	20		0.041	1.10	12.6	2.72	<0.6					
2P033104	20040330	200406225	<2	22		0.046	1.07	11.9	2.71	<0.6					
F033104	20040330	200406226	~463	693	108	19.9	83.8	0.065	18.4	408	316				
1P033104C	20040331	200406227												<1	<1
2P033104C	20040331	200406228												4	<1
F033104C	20040331	200406229												$30x10^6$	$\sim 1x10^6$
1AO033104	20040331	200406230										5870	4270		
2AO033104	20040331	200406231										5940	4290		
1P040204	20040401	200406382	<2	21		0.061	1.19	13.1	3.46	1					
2P040204	20040401	200406383	<2	22		0.106	1.17	14.2	2.78	<0.6					
F040204	20040401	200406384	271	386	162	25.9	46.9	0.070	8.49	132	92				
1AO040204	20040402	200406385										6700	4910		
1MT040204	20040402	200406386										7980	5840		
2AO040204	20040402	200406387										6580	4720		
2MT040204	20040402	200406382										7940	5680		
1P040504	20040404	200406569	<2	23		0.043	1.08	16.6	2.54	<0.6					

2P040504	20040404	200406570	<2	19		0.057	1.12	17.3	0.67	<0.6					
F040504	20040404	200406571	~408	376	182	40.6	58.9	0.017	8.58	124	96				
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1

Table 49. GBWWTP lab report for MBR (April 5 to April 11, 2004).

SOURCE	DATE	Goldbar ID	TESTS												
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL
1PR040504	20040405	200406572										4010	3050		
1AE040504	20040405	200406573										4040	3130		
1AN040504	20040405	200406574										6020	4530		
1AO040504	20040405	200406575										7240	5420		
1MT040504	20040405	200406576										8380	6170		
2AE040504	20040405	200406577										3160	2480		
2AN040504	20040405	200406578										5550	4160		
2AO040504	20040405	200406579										7020	5220		
2MT040504	20040405	200406580										8580	6270		
1P040704	20040406	200406757	<2	26		<0.013	1.24	11.1	0.82	1					
2P040704	20040406	200406758	<2	24		<0.013	1.15	10.6	0.87	<0.6					
F040704	20040406	200406759	880	872	155	35.6	90.8	<0.006	31.10	690	530				
1P040704C	20040407	200406760												<1	<1
2P040704C	20040407	200406761												<	<1
F040704C	20040407	200406762												14.0×10^6	1.40×10^6
1AO040704	20040407	200406763										8200	6090		

1MT040704	20040407	200406764										9980	7270		
2AO040704	20040407	200406765										7810	5720		
2MT040704	20040407	200406766										9680	7092		
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1

Table 50. GBWWTP lab report for MBR (April 12 to April 17, 2004).

SOURCE	DATE	Goldbar ID	TESTS												
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL
1P041404	20040413	200407135	<2	32		<0.013	1.22	12.6	2.08	<0.6					
2P041404	20040413	200407136	<2	32		<0.013	1.20	13.3	1.79	<0.6					
F041404	20040414	200407137	500	552	211	34.3	60.2	0.010	16.20	276	220				
1P041404C	20040414	200407138												<1	<1
2P041404C	20040414	200407139												7	<1
F041404C	20040414	200407140												20.0×10^6	$\sim 0.66 \times 10^6$
1PR041404	20040414	200407141										4210	3270		
1AE041404	20040414	200407142										4140	3230		
1AN041404	20040414	200407143										6340	4810		
1AO041404	20040414	200407144										7270	5500		
1MT041404	20040414	200407145										8580	6410		
2AE041404	20040414	200407146										2930	2340		
2AN041404	20040414	200407147										4850	3700		
2AO041404	20040414	200407148										5810	4340		
2MT041404	20040414	200407149										6900	5140		

1P041604	20040416	200407281	<2	28		<0.013	0.90	12.9	0.85	<0.6					
2P041604	20040416	200407282	<2	30		<0.013	0.85	11.2	0.65	<0.6					
F041604	20040416	200407283	163	437	119	18.772	39.2	<0.006	7.15	264	144				
1AO041604	20040416	200407284										5050	3720		
1MT041604	20040416	200407285										6180	3980		
2AO041604	20040416	200407286										5000	2340		
2MT041604	20040416	200407287										5640	2150		
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1

Table 51. GBWWTP lab report for MBR (April 18 to April 24, 2004).

SOURCE	DATE	Goldbar ID	TESTS												
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL
1P041904	20040418	200407492	<2	31		<0.013	0.99	17.3	3.51	1					
2P041904	20040418	200407493	<2	27		0.025	1.03	15.9	2.84	1					
F041904	20040418	200407494	204	140	368	33.2	46.0	<0.006	8.22	114	86				
1PR041904	20040419	200407495										2660	2020		
1AE041904	20040419	200407496										2640	2000		
1AN041904	20040419	200407497										3920	2910		
1AO041904	20040419	200407498										4680	3470		
1MT041904	20040419	200407499										5450	4050		
2AE041904	20040419	200407500										1920	1460		
2AN041904	20040419	200407501										3550	2620		
2AO041904	20040419	200407502										5000	3670		
2MT041904	20040419	200407503										5460	4030		

1P042104	20040420	200407666	<2	24		0.032	1.06	11.3	2.25	<0.6					
2P042104	20040420	200407667	<2	27		0.036	0.98	11.0	2.40	<0.6					
F042104	20040420	200407668	454	586	217	36.8	62.3	0.053	13.8	274	208				
1P042104C	20040421	200407669												<1	<1
2P042104C	20040421	200407670												<1	<1
F042104C	20040421	200407671												20 X 10^6	2.9 X 10^6
1AO042104	20040421	200407672										6180	4620		
1MT042104	20040421	200407673										7340	5460		
2AO042104	20040421	200407674										6280	4630		
2MT042104	20040421	200407675										7360	5490		
1P042304	20040422	200407809	<2	25		0.028	1.07	13.9	0.73	<0.6					
2P042304	20040422	200407810	<2	36		0.027	1.13	14.0	0.93	<0.6					
F042304	20040422	200407811	424	437	162	37.6	51.9	<0.006	8.27	132	110				
1AO042304	20040423	200407812										6370	4780		
1MT042304	20040423	200407813										7660	5780		
2AO042304	20040423	200407814										6620	4940		
2MT042304	20040423	200407815										7590	5670		
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1

Table 52. GBWWTP lab report for MBR (April 25 to April 29, 2004).

SOURCE	DATE	Goldbar ID	TESTS												
			BOD mg/L	COD mg/L	COD-H-sol mg/L	N-NH3 mg/L	N-TKN mg/L	N-TOX mg/L	TP mg/L	TSS mg/L	VSS mg/L	TSS-P mg/L	VSS-P mg/L	CO-T-M cfu/100mL	CO-F-M cfu/100mL
1P042604	20040425	200407989	<2	31		0.028	1.20	14.1	0.99	<0.6					
2P042604	20040425	200407990	<2	28		0.025	1.14	15.3	2.47	1					

F042604	20040425	200407991	178	377	155	37.1	51.4	0.018	8.49	110	89				
1PR042604	20040426	200407992										3600	2880		
1AE042604	20040426	200407993										5890	4520		
1AN042604	20040426	200407994										4990	3850		
1AO042604	20040426	200407995										6840	5240		
1MT042604	20040426	200407996										3110	2500		
2AE042604	20040426	200407997										4760	3590		
2AN042604	20040426	200407998										5760	4370		
2AO042604	20040426	200407999										6580	4940		
2MT042604	20040426	200408000										3850	3080		
1P042804	20040427	200408125	<2	40		0.016	1.14	9.29	0.64	<0.6					
2P042804	20040427	200408126	<2	32		0.026	1.13	8.02	1.04	<0.6					
F042804	20040427	200408127	130	491	201	32.9	49.3	0.021	9.66	202	150				
1P042804C	20040428	200408128												<1	<1
2P042804C	20040428	200408129												2	<1
F042804C	20040428	200408130												~9.1 x 10^6	1.8 x 10^6
1AO042804	20040428	200408131										5970	4540		
1MT042804	20040428	200408132										6540	4820		
2AO042804	20040428	200408133										5270	3940		
2MT042804	20040428	200408134										7120	5430		
1P042904	20040429	200408210	<2	28		0.031	1.05	9.22	4.81	1					
2P042904	20040429	200408211	<2	28		0.022	1.05	9.35	3.46	<0.6					
F042904	20040429	200408212	240	458	179	37.1	43.7	0.080	10.3	120	100				
1AO042904	20040429	200408215										4240	2680		
2AO042904	20040429	200408216										3480	2030		
	Limit of Detection		2.0	2.0/5.0	2.0/5.0	0.013	0.032	0.006	0.016	0.6	-	-	-	1	1

Table 53. GBWWTP report of VFA in MBR-Feed (Feb. 17 to Apr. 22, 2004).

Date	Experiment Day	Feed	Acetic acid (mg/L)	Propionic (mg/L)	Buryric (mg/L)
20040217	21	F022004	64	11	10
20040224	28	F022504	37	14	10
20040302	35	F030304	52	12	10
20040309	42	F031004	10	11	10
20040316	49	F031704	47	11	10
20040318	51	F031904	10	11	10
20040325	58	F032604	11	11	10
20040401	65	F040204	10	11	10
20040404	68	F040504	10	11	10
20040415	79	F041604	10	11	10
20040422	86	F042304	10	11	10